Theory Perspective

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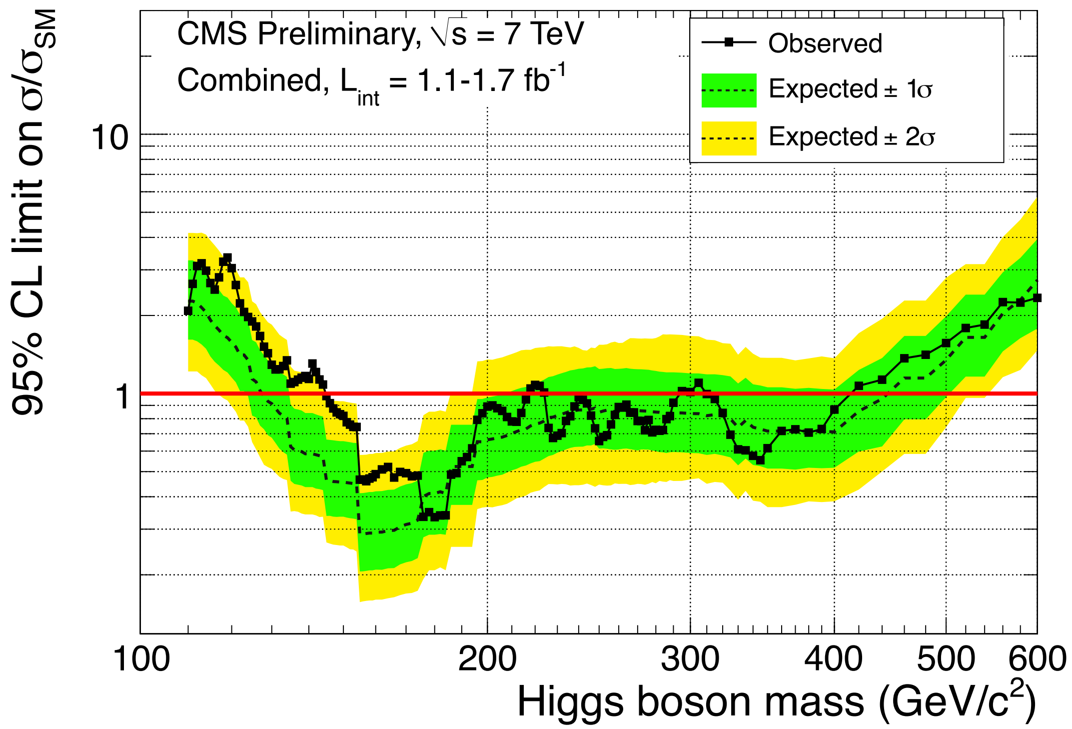
Physics at the Weak Scale : Motivation

- Electroweak Symmetry Breaking and the Hierarchy Problem.
- Low Energy Supersymmetry, Technicolor, Extra Dimensions...

- Origin of Matter
- Dark Matter (Weak scale annihilation cross section)
- Electroweak Baryogenesis (New states and CP-violation)

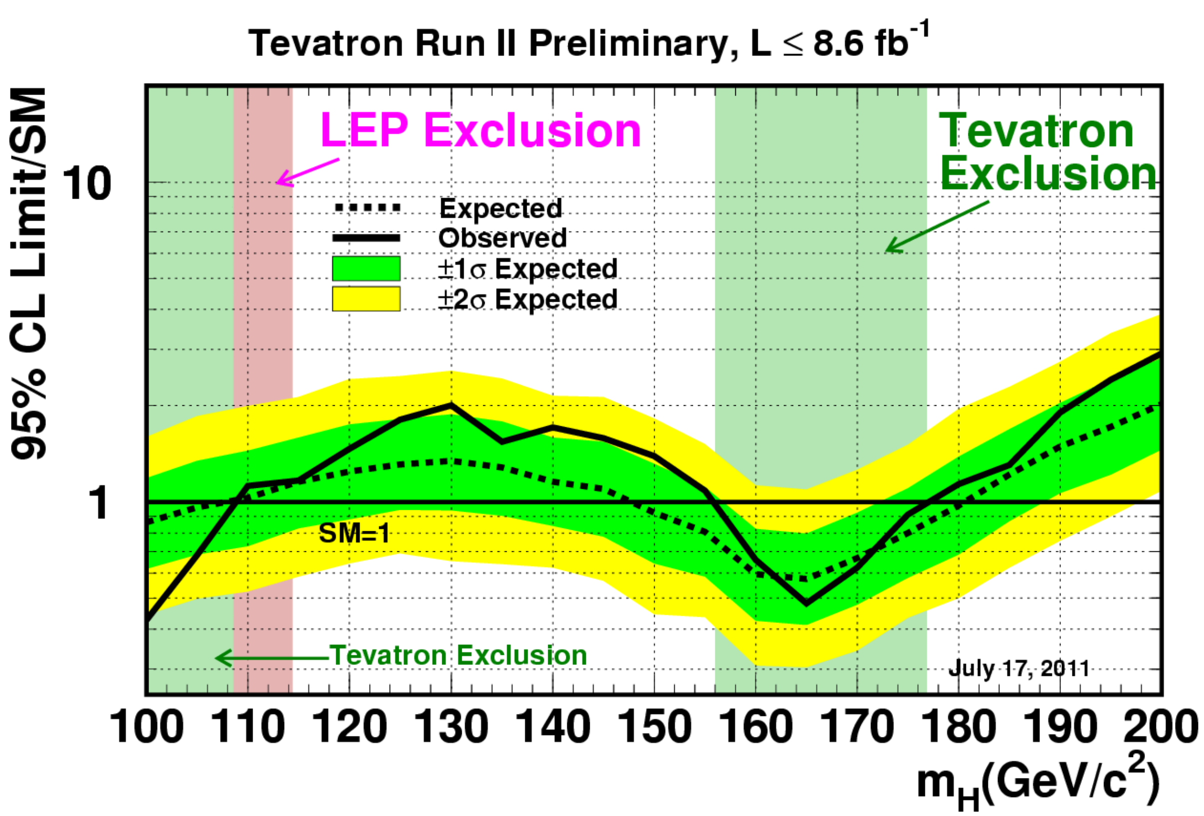
- Explanation of Observed Experimental Anomalies



We are leaving in exciting times:

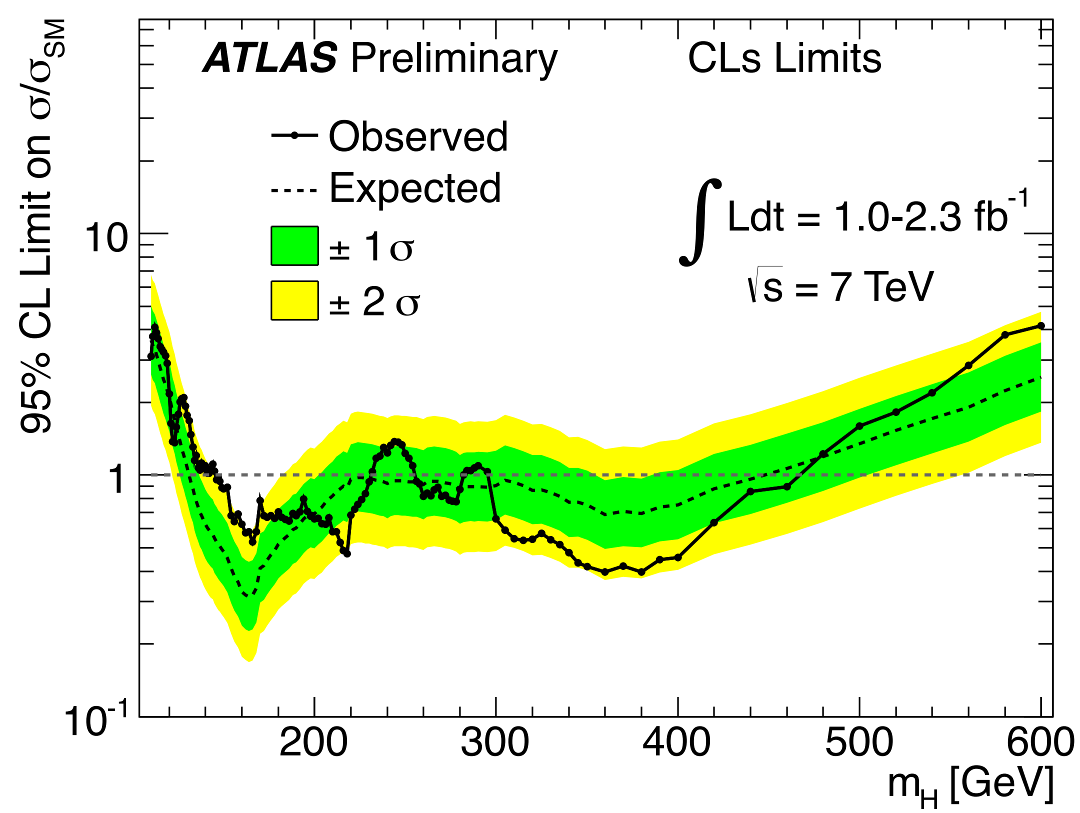
Experiments are starting to test the SM Higgs above the LEP limit, leading to interesting exclusion bounds on its mass.

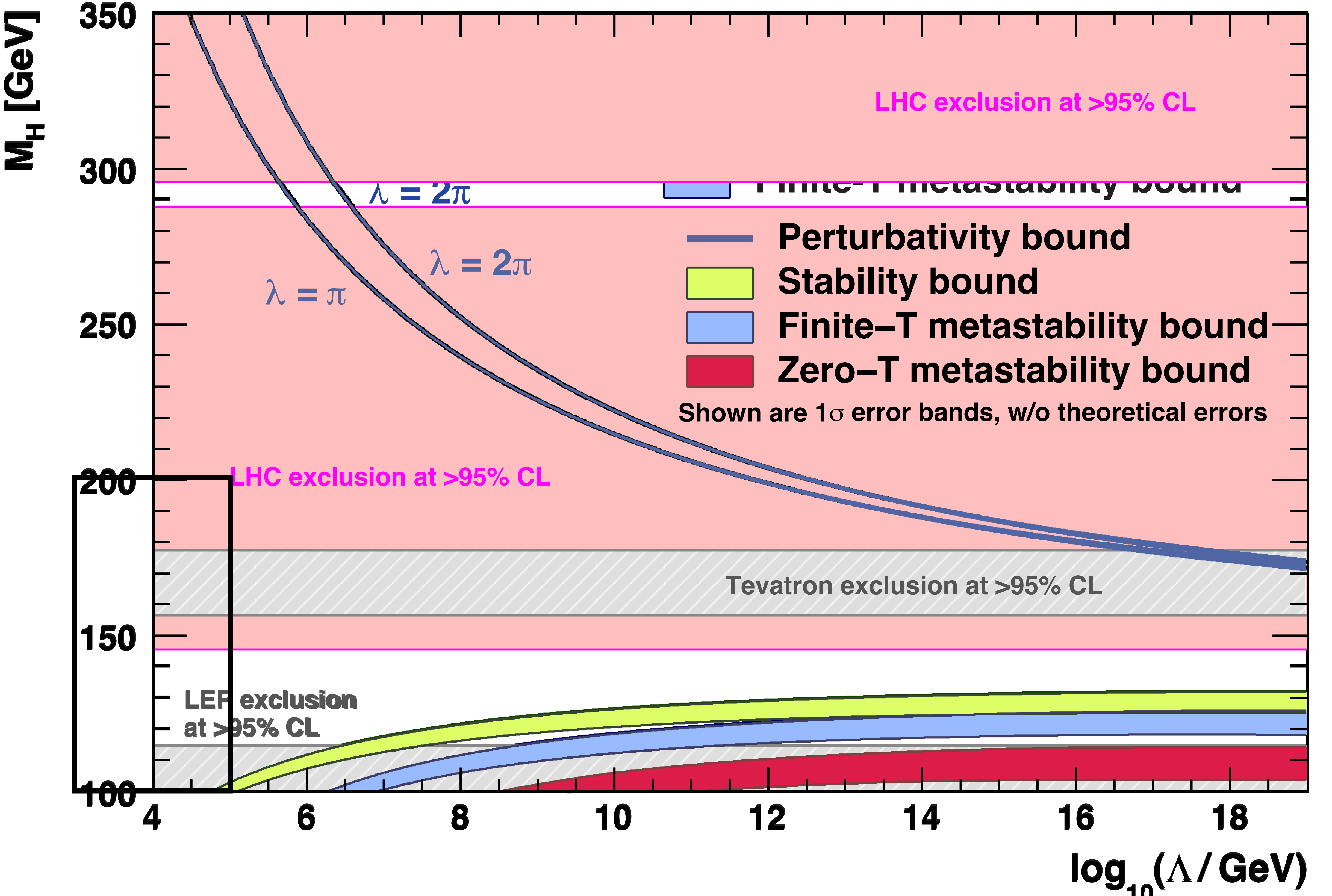
A light SM-like Higgs, is beginning to be probed by present data. More information from the LHC will be available as early as next week.



Observed Exclusion : 100-109 and 156-177 GeV/c^2

Expected Exclusion : 100-108 and 148-181 GeV/c^2





Harigaya, Matsumoto, HM

Deformation of the SM Higgs: current constraints

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

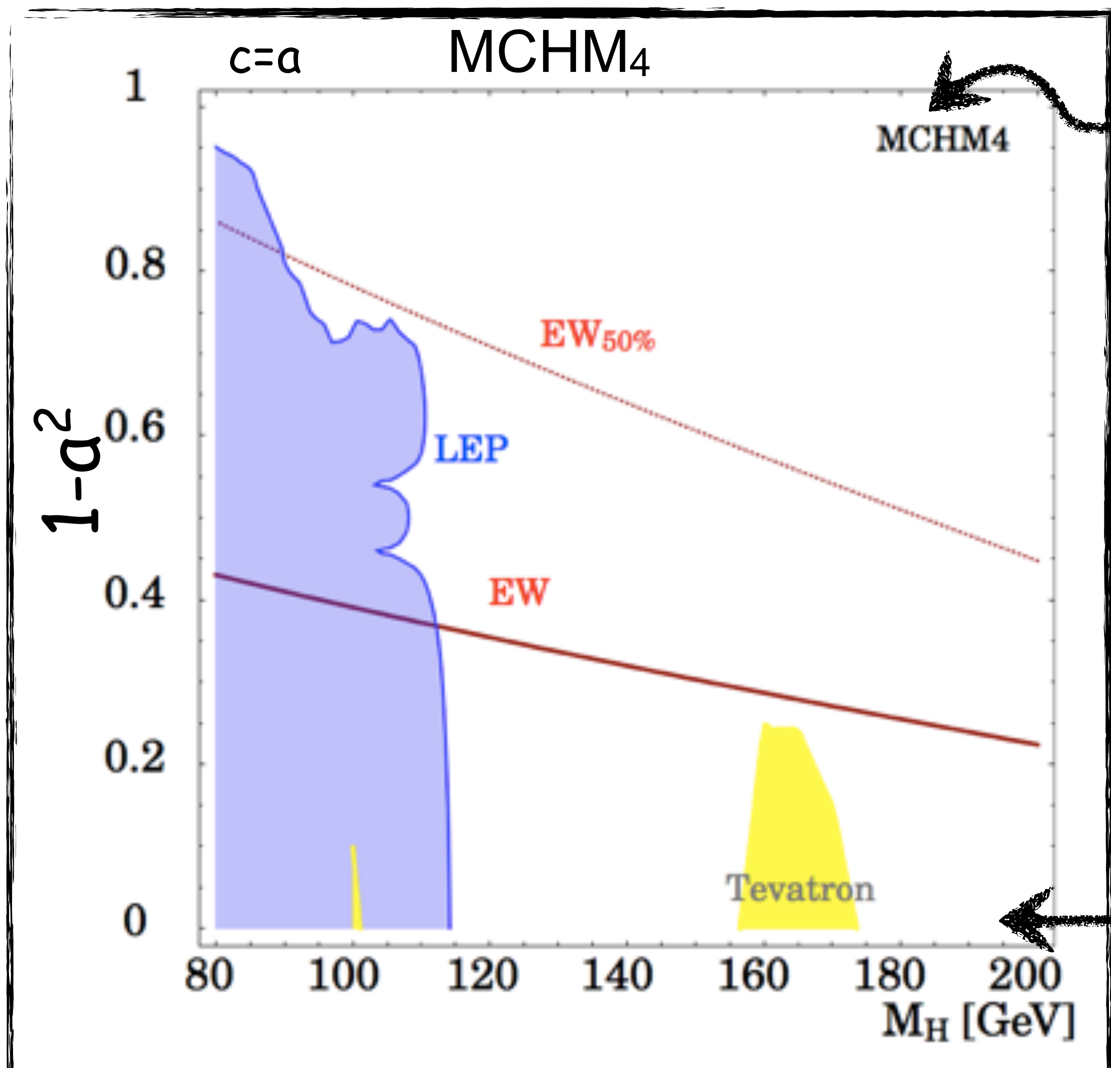
Grojean

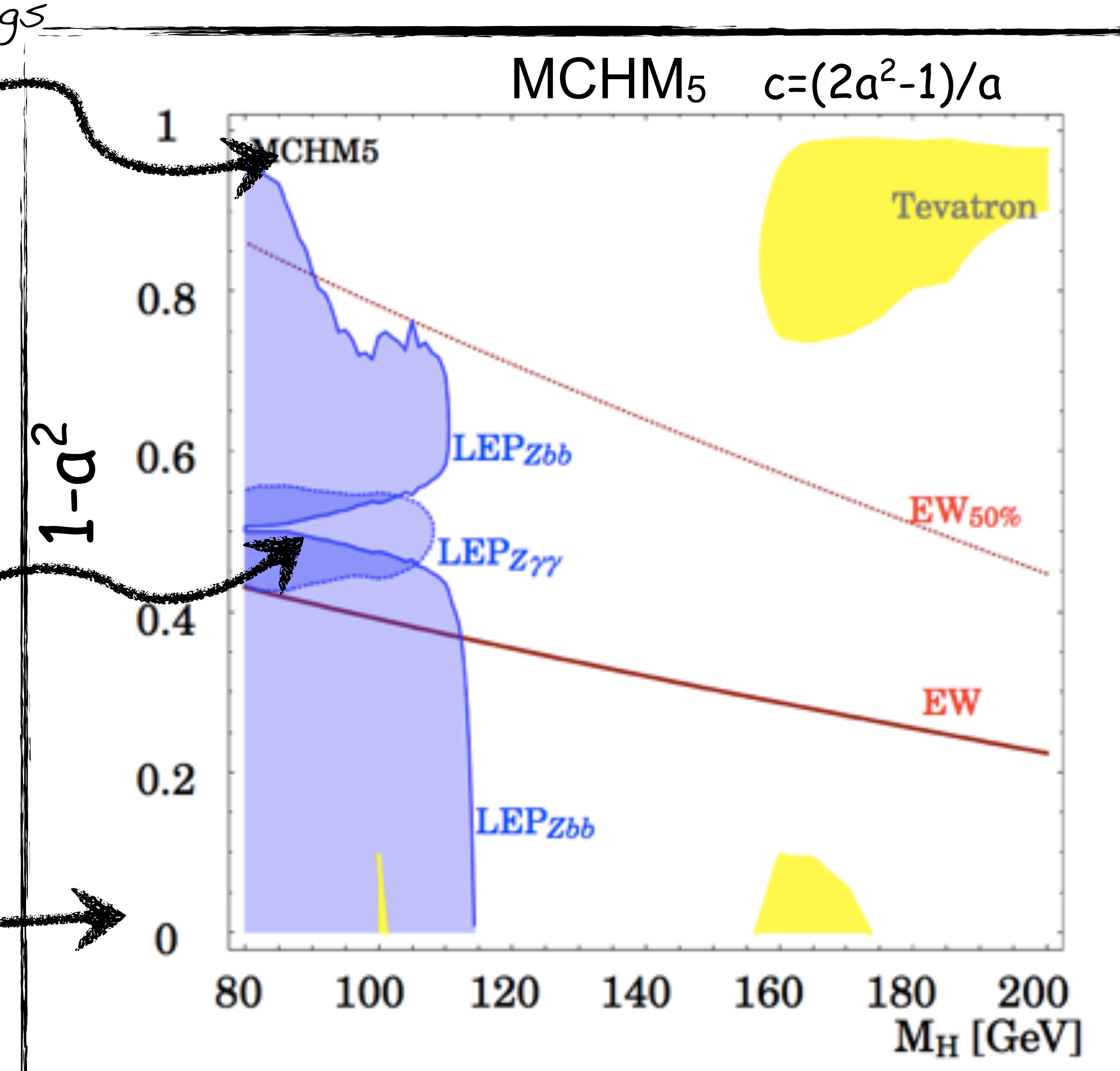
SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a' (and marginally 'c')

Espinosa, Grojean, Muehlleitner '10

gaugephobic Higgs





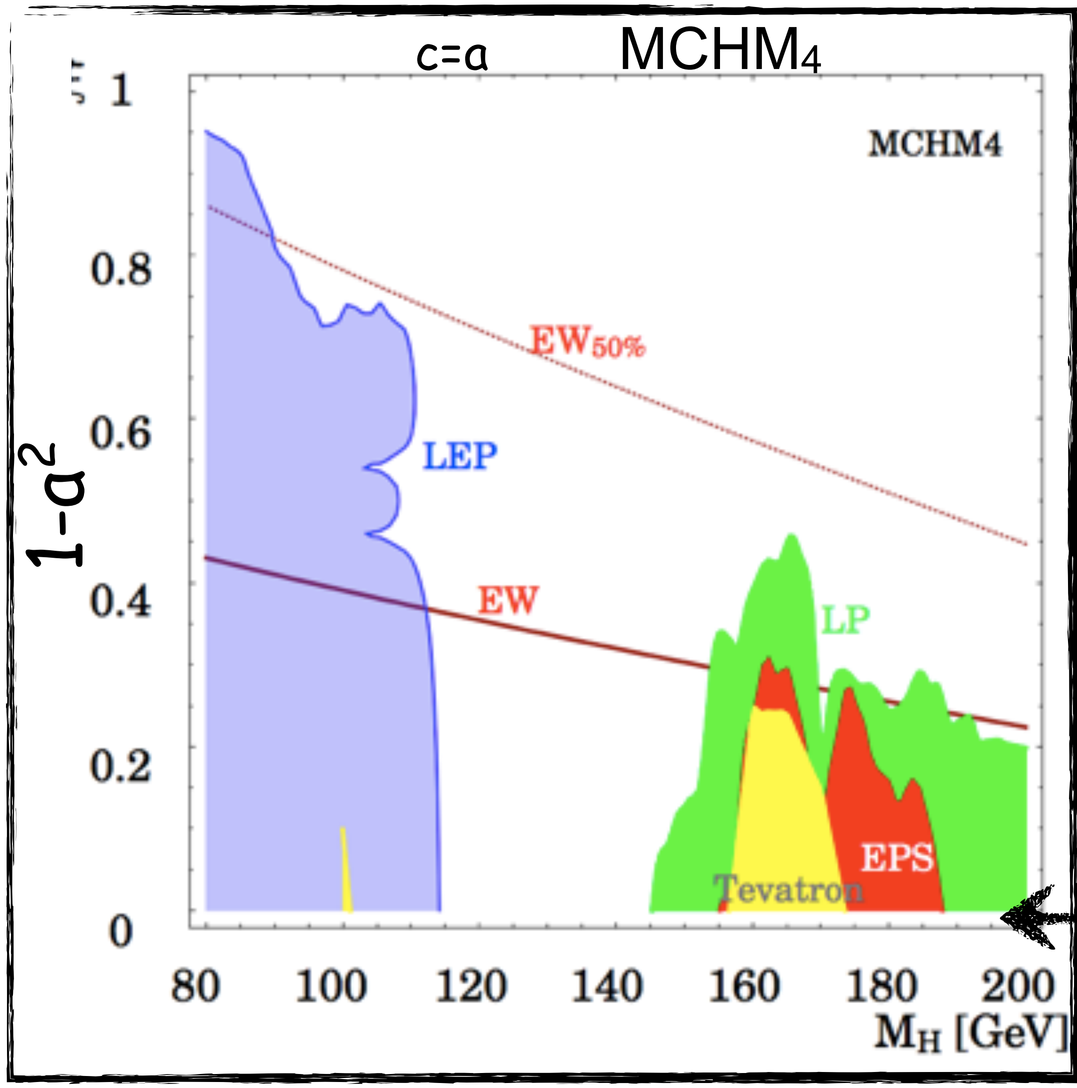
fermiophobic Higgs

SM limits

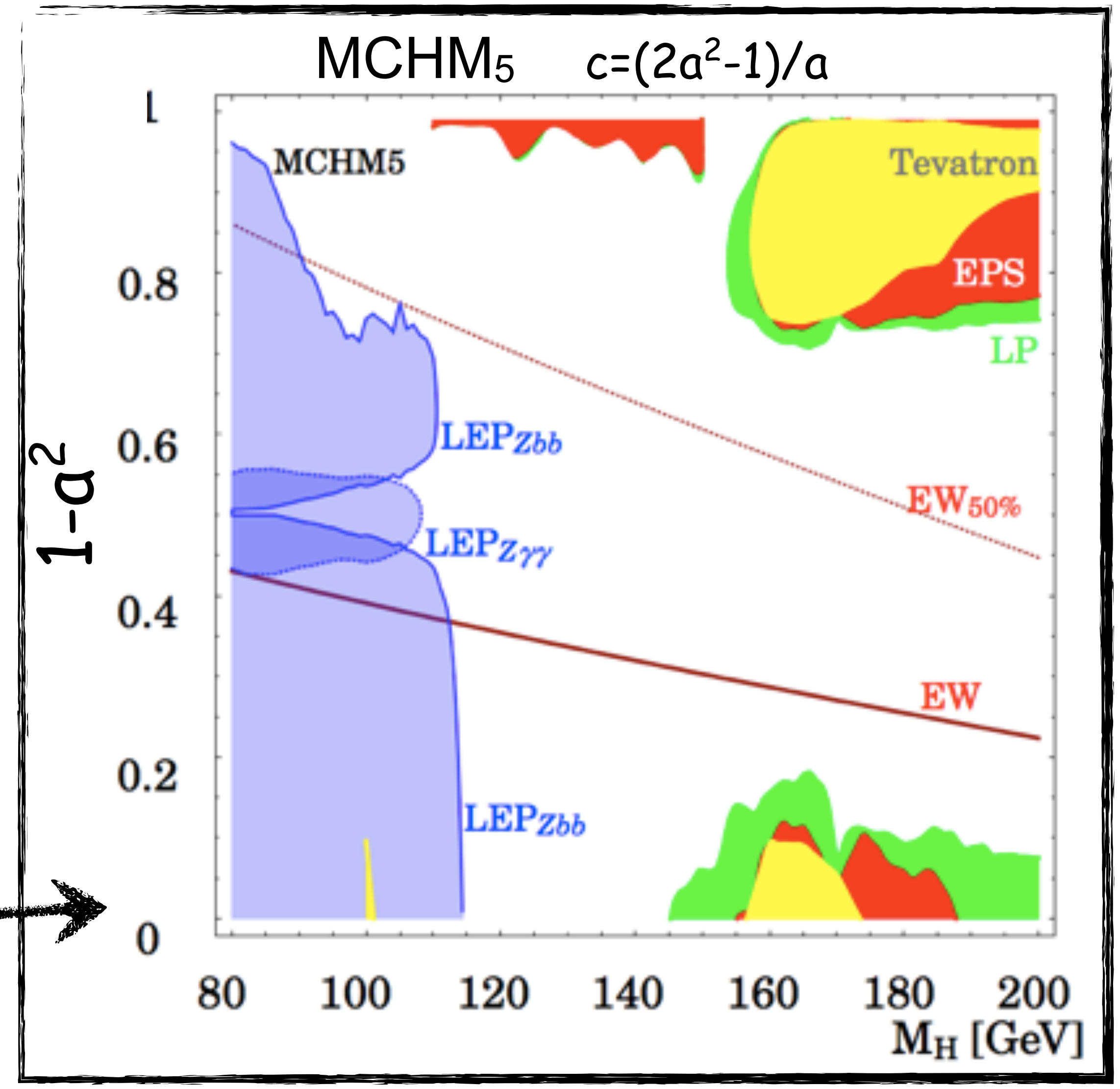
Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



SM limits



LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

Physics Beyond the SM : Supersymmetry

Supersymmetry ?

Theoretical arguments in favor:

1. Longstanding: technical naturalness, precision electroweak, unification, dark matter.
2. More recent: vast array of new models for *dynamical supersymmetry breaking*, exploiting *metastability* (ISS). Dynamical Supersymmetry Breaking Generic.
3. Arguments even within landscape, which might favor low energy supersymmetry. In fact, *landscape provides a potentially more sophisticated understanding of naturalness.*

M. Dine

“In simplified models, masses of gluinos and squarks should be heavier than about 1 TeV”

Feng

10 Isn’t SUSY is excluded by the LHC?

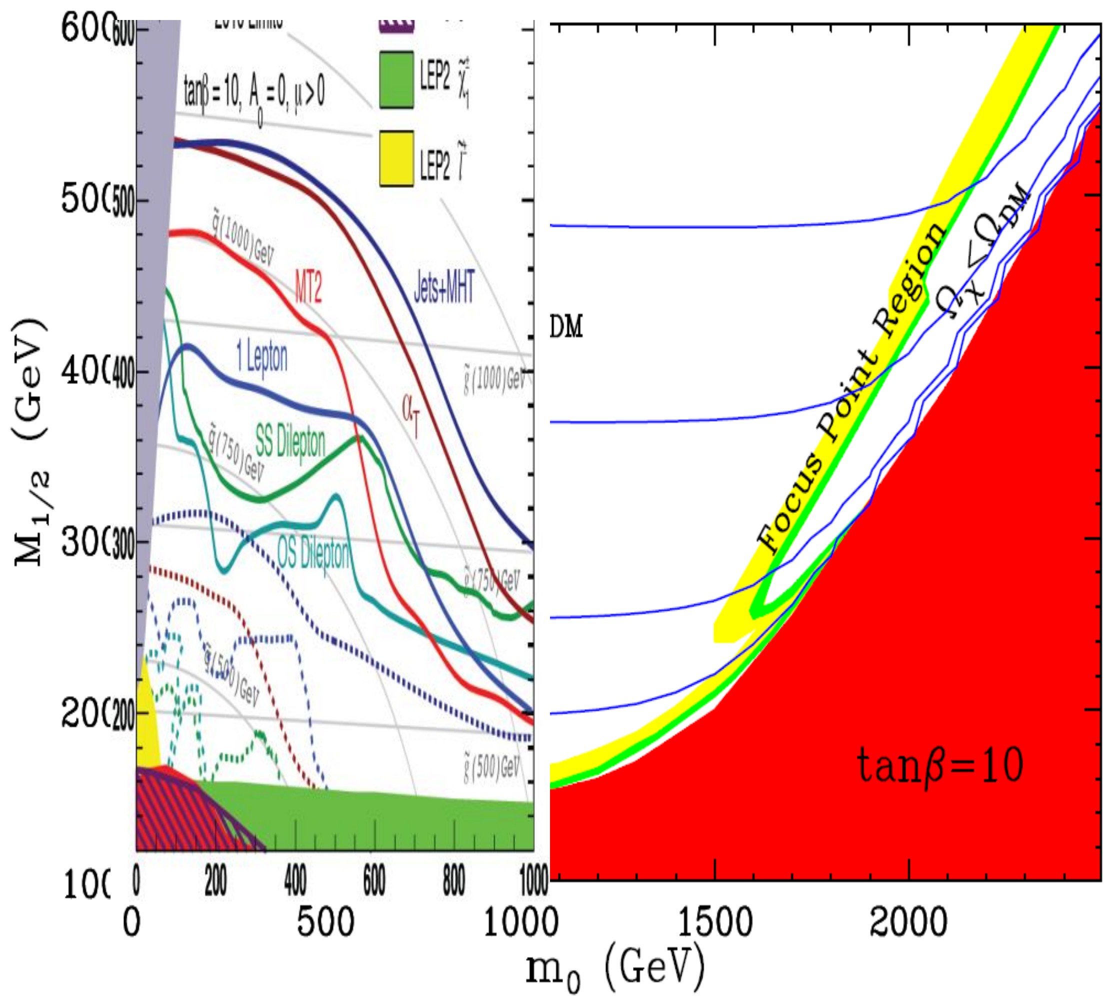
– The last time I heard so many levels of misunderstanding packed into such a short question, it was “Isn’t evolution just a theory?”

9 Isn’t mSUGRA/CMSSM excluded by the LHC?

– No – look at the plot! It’s fantastic to think about compressed SUSY, etc. if you want, but mSUGRA is doing just fine.

8 Isn’t focus point SUSY a pretty thin band of parameter space?

– So is every cosmologically preferred region. Those darn cosmologists!



Friday, September 2, 2011

4 But why should the superpartners be so heavy?

- EDMs, proton decay and coupling constant unification, and the Higgs mass all point toward multi-TeV scalars.

3 Isn't FP SUSY excluded by dark matter?

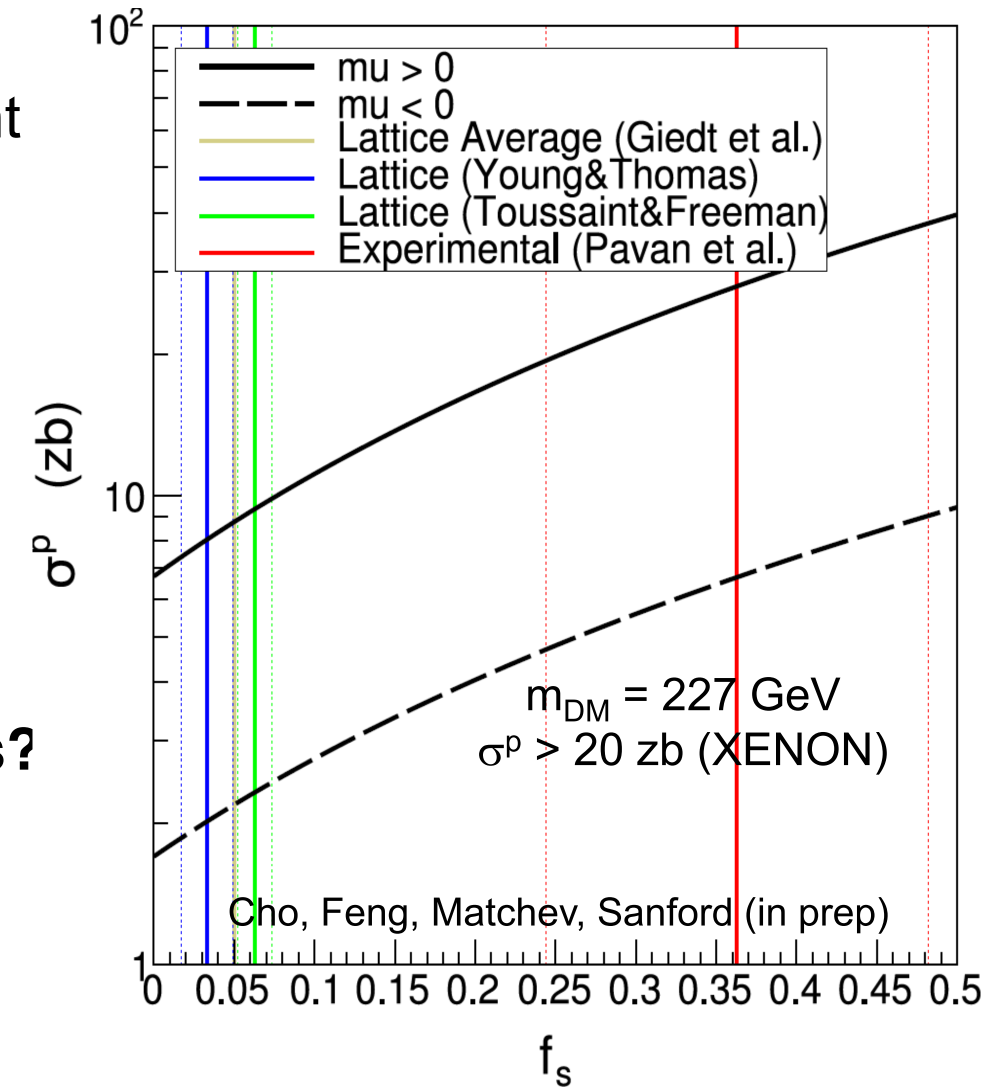
- It depends on the strange quark content and the sign of mu.

2 Didn't many people think SUSY should have been below a TeV?

- So what? Anyway, they might be right (see 9).

1 Doesn't $(g-2)_\mu$ require light superpartners?

- Yes. And if you think smuons and squarks have to be degenerate, I have some beautiful ocean front property in Florida to sell you.



- **Minimal Flavour Violating Approach to Flavour and CP**

- The MFV:

$$m_0(M_{\rm MFV})\,,\ \ m_{1/2}(M_{\rm MFV})\,,\ \ A(M_{\rm MFV})\,;\ \ \tan\beta(m_t)\,,\ \ M_Z\ \ \text{up to}\,{\rm sign}(\mu)$$

with real and positive m_0, $m_{1/2}$, and A

- Next to MFV:

$$m_0(M_{\rm MFV})\,,\ \ m_{1/2}(M_{\rm MFV})\,,\ \ A(M_{\rm MFV})\,;\ \ \tan\beta(m_t)\,,\ \ M_Z$$

with complex $m_{1/2}$ and A

- What is the maximal extension to MFV?

- Breaking of the $[SU(3) \otimes U(1)]^5$ flavour symmetries in the MSSM:

[R. S. Chivukula and H. Georgi, PLB188 (1987) 99;
G. D'Ambrosio, G. F. Giudice, G. Isidori, A. Strumia, NPB645 (2002) 155;
Generalization of GIM mechanism: S.L. Glashow, J. Iliopoulos, L. Maiani, PRD2 (1970) 1285.]

$$\begin{aligned}
\mathbf{h}_{u,d} &\to \mathbf{U}^{\dagger}_{U,D}\, \mathbf{h}_{u,d}\, \mathbf{U}_Q\,, \qquad \mathbf{h}_e \to \mathbf{U}^{\dagger}_{E}\, \mathbf{h}_e\, \mathbf{U}_L\,,\\
\widetilde{\mathbf{M}}^2_{Q,L,U,D,E} &\to \mathbf{U}^{\dagger}_{Q,L,U,D,E}\, \widetilde{\mathbf{M}}^2_{Q,L,U,D,E}\, \mathbf{U}_{Q,L,U,D,E}\,,\\
\mathbf{a}_{u,d} &\to \mathbf{U}^{\dagger}_{U,D}\, \mathbf{a}_{u,d}\, \mathbf{U}_Q\,, \qquad \mathbf{a}_e \to \mathbf{U}^{\dagger}_{E}\, \mathbf{a}_e\, \mathbf{U}_L\,.
\end{aligned}$$

- Maximal CP and Minimal Flavour Violation (MCPMFV)

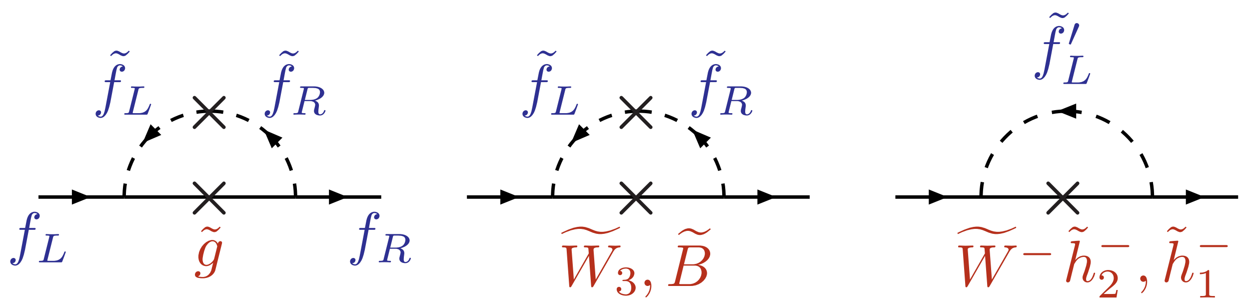
[e.g. J. Ellis, J. S. Lee, A. P., PRD76 (2007) 115011.]

$$M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \quad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} = \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \quad \mathbf{A}_{u,d,e} = A_{u,d,e}\,\mathbf{1}_3$$

$$3 \oplus 3 \qquad 2 \qquad 5 \qquad 3 \oplus 3$$

$$\boxed{13 \oplus 6 = 19 \text{ Parameters !}}$$

- **EDMs in the MSSM**



with $f = e,\ u,\ d$

$$\left(\frac{d_f}{e}\right)^{1-\mathrm{loop}} \sim (10^{-25}\ \mathrm{cm}) \times \frac{\{\mathrm{Im}\, m_\lambda,\ \mathrm{Im}\, A_f\}}{\max(M_{\tilde{f}}, m_\lambda)} \left(\frac{1\ \mathrm{TeV}}{\max(M_{\tilde{f}}, m_\lambda)}\right)^2 \left(\frac{m_f}{10\ \mathrm{MeV}}\right)$$

Schemes for resolving the 1-loop CP crisis:

- $\mathrm{Im}\, m_\lambda / |m_\lambda|,\ \mathrm{Im}\, A_f / |A_f| \lesssim 10^{-3}$; $M_{\tilde{f}}, m_\lambda \sim 200$ GeV

- CP phases ~ 1, <u>but</u> $M_{\tilde{f}} \gtrsim$ 5–10 TeV, for $\tilde{f} = \tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}_L$

- The MSSM with MFV extended to MCPMFV is an interesting framework for studying New Physics.
  It contains 19 parameters = 13 CP-even $\oplus$ 6 CP-odd.

- Non-observation of Thallium, neutron and Mercury EDMs give strict constraints on 3 combinations of the 6 soft CP-odd phases of MFV-type scenarios.

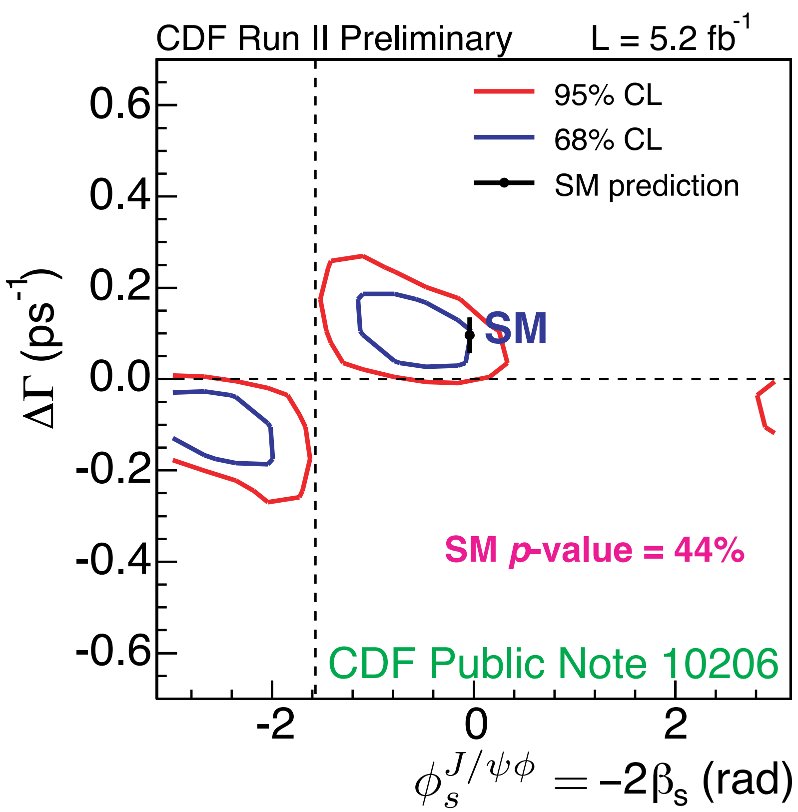
- Geometric approach introduced for maximazing CP observables in the small phase approximation.

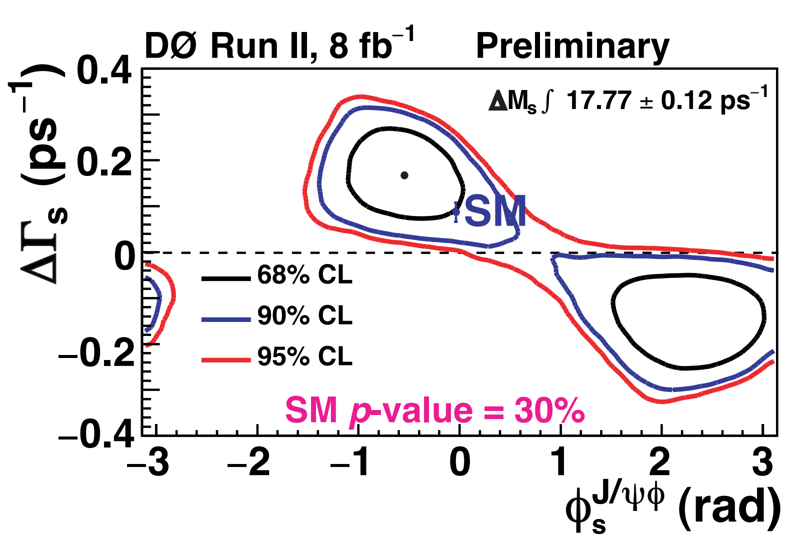
- Interplay of future EDM observables (Deuteron and Radium) will further constrain soft CP violation in SUSY, including $\theta_{\rm QCD}$.
  $\Longrightarrow$ Pushing the limit to $\theta_{\rm QCD} \lesssim 10^{-12}$

The drama of Lepton-Photon 2011

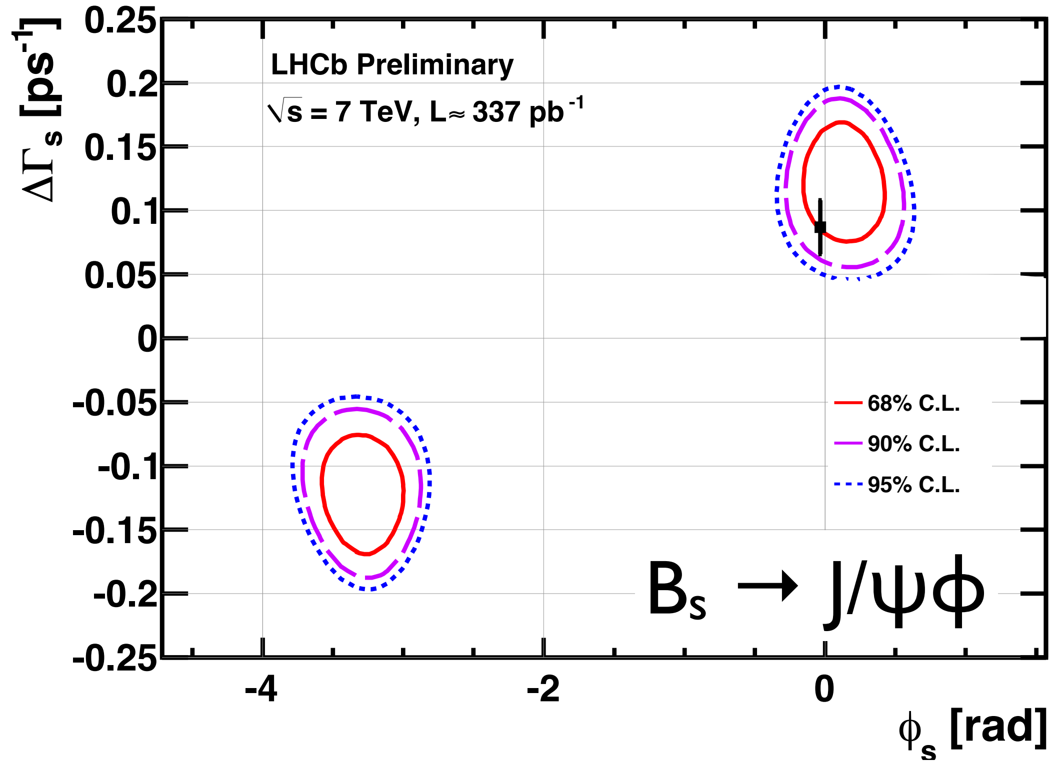
Neubert

Tevatron results for Φ_s





LHCb result for Φ_s at LP11



$\phi_s = 0.13 \pm 0.18 \text{ (stat)} \pm 0.07 \text{ (syst)}$

$\Delta\Gamma_s = 0.123 \pm 0.029 \text{ (stat)} \pm 0.008 \text{ (syst) ps}^{-1}$

When combined with $B_s \to J/\psi\, f_0$:

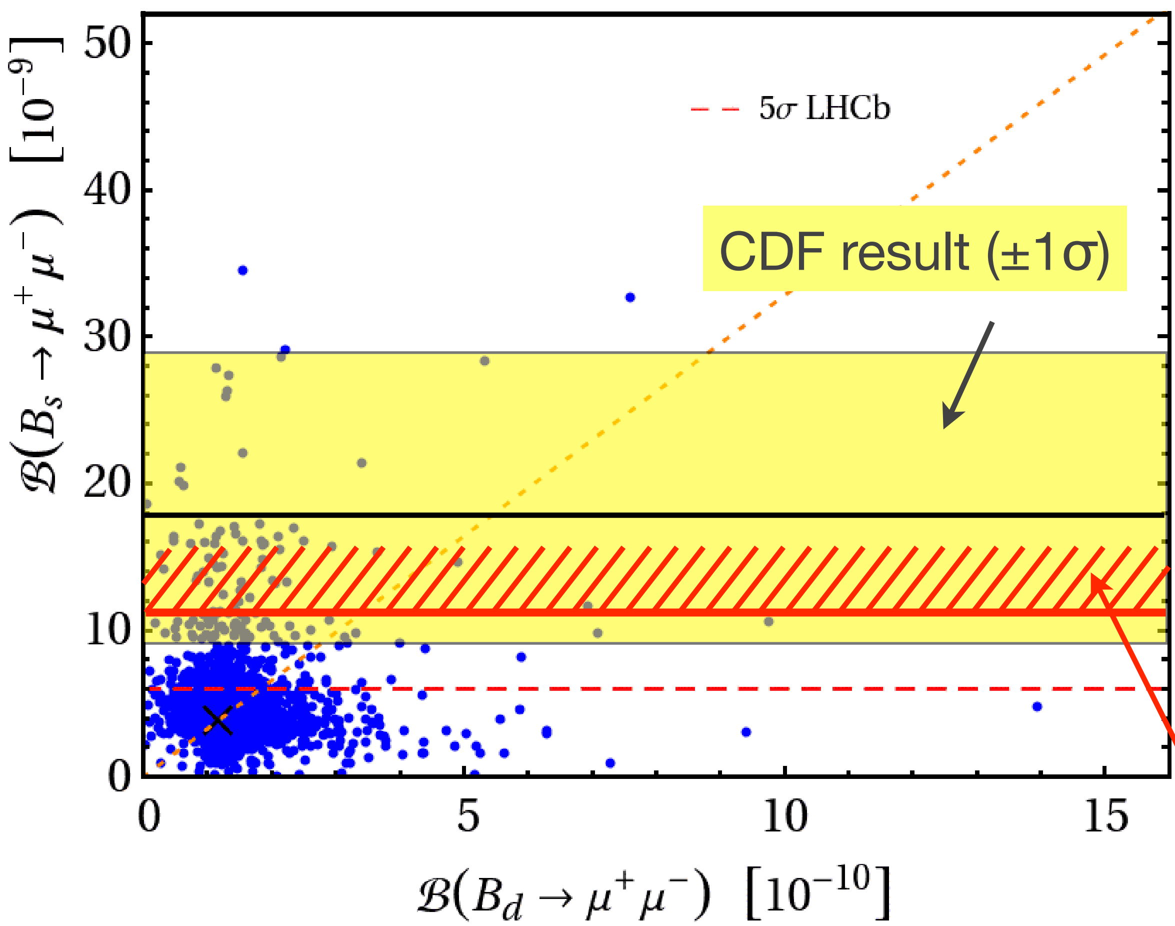
$\phi_s = 0.03 \pm 0.16 \pm 0.07$ rad

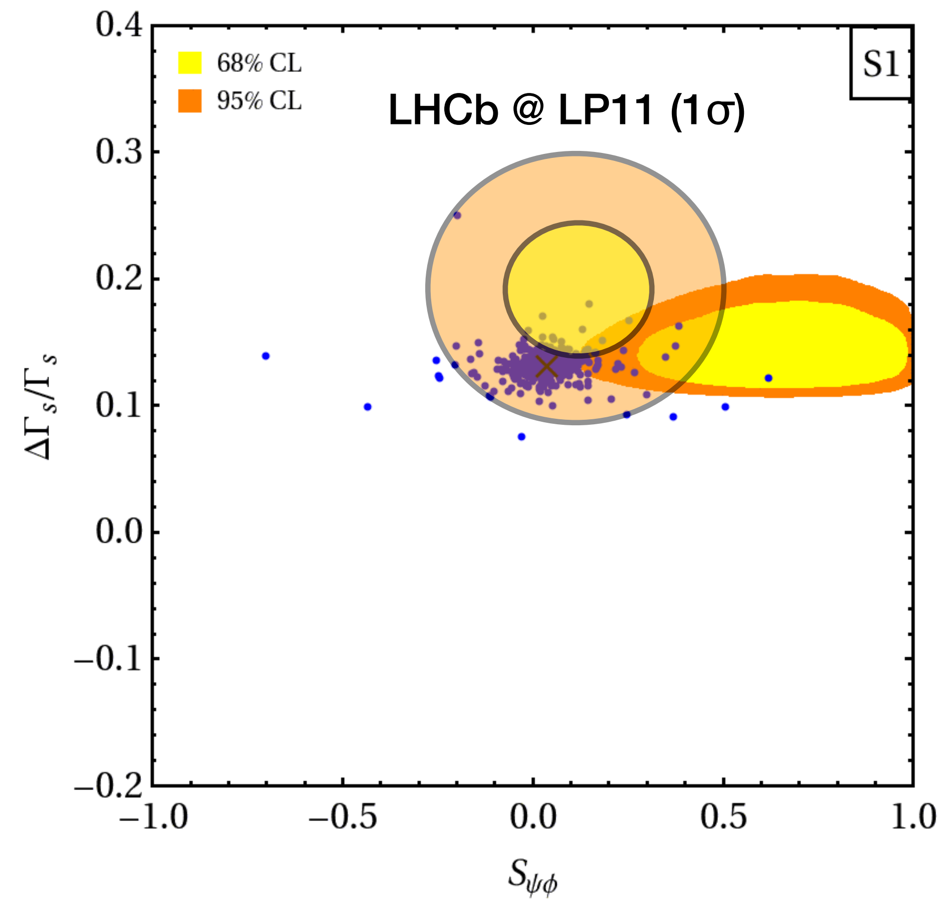
SM: $\Phi_s = -0.004$

No obvious signs of non-standard CP violation

Theoretical predictions: Randall-Sundrum model

Both rare modes $B_{d,s} \to \mu^+\mu^-$ can be significantly enhanced over their SM values:





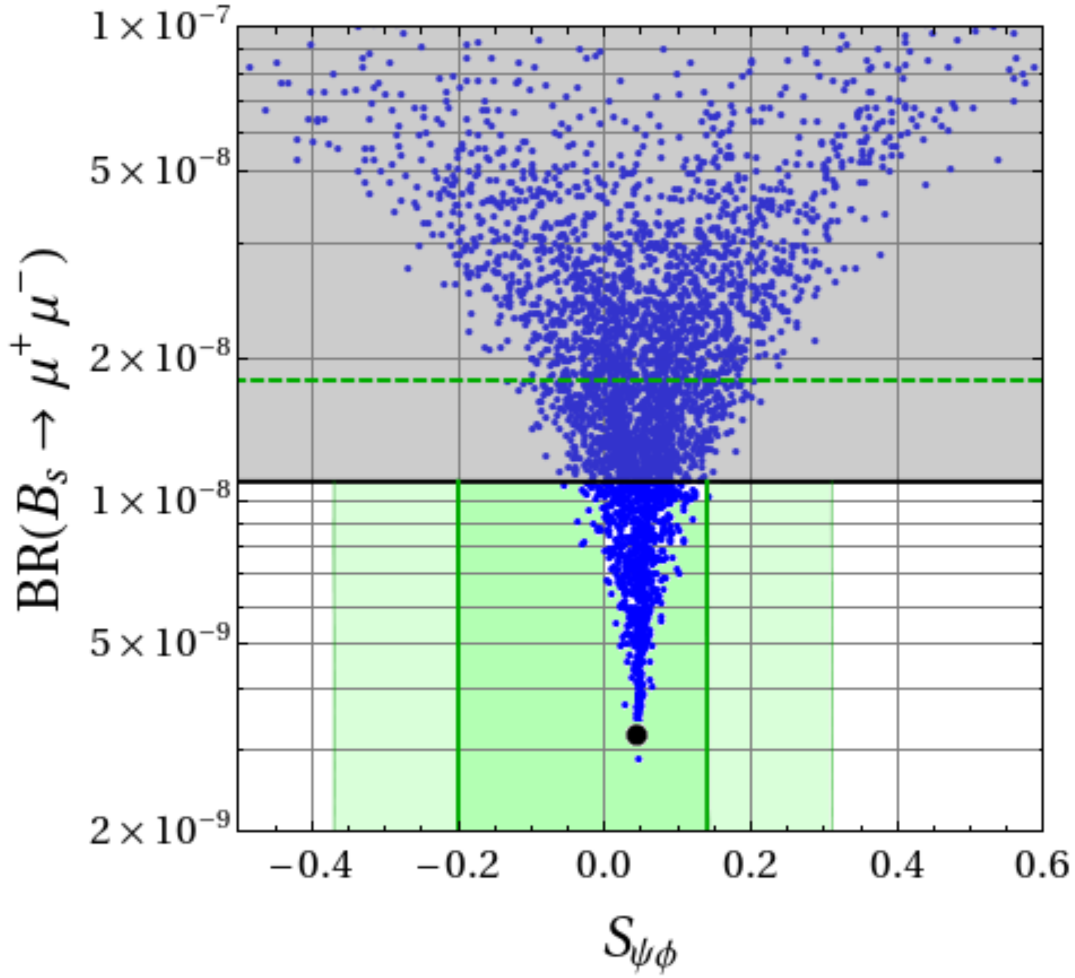
LHCb +CMS upper bound (95% CL)

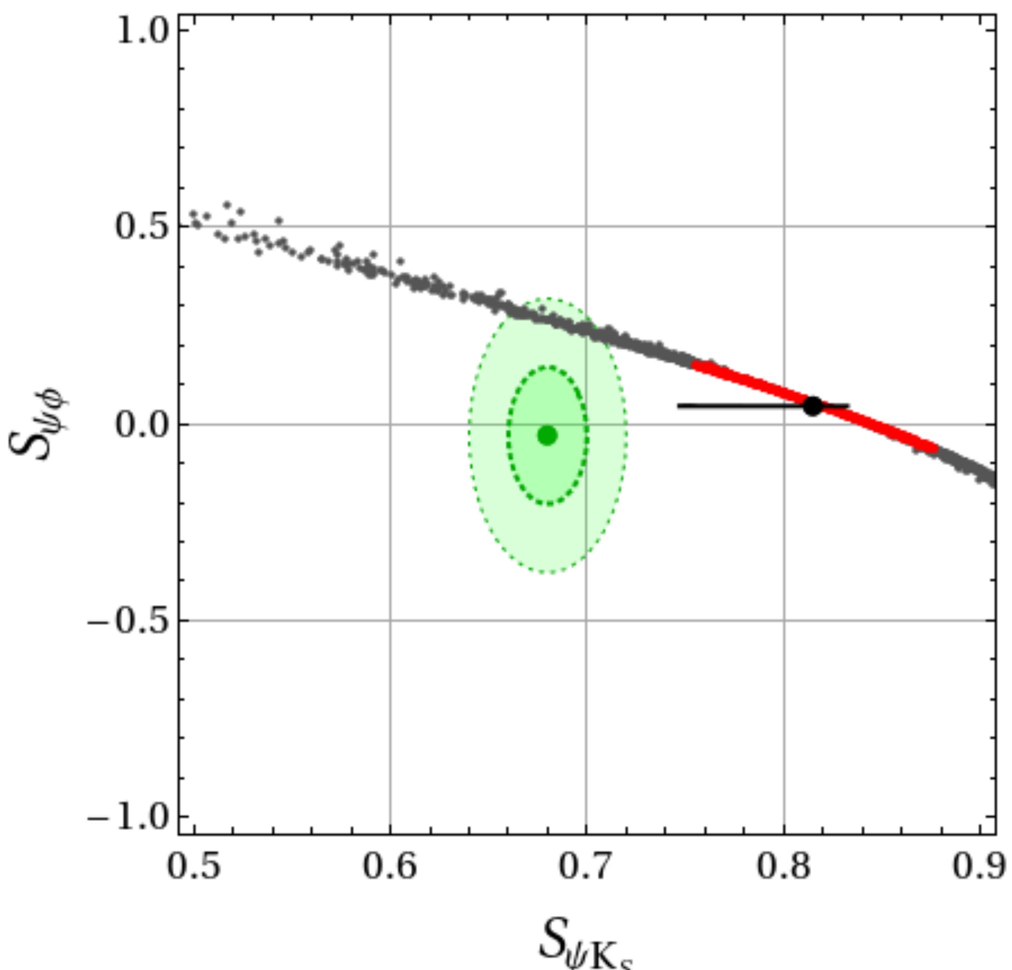
Bauer, Casagrande, Haisch, MN (2009);
see also: Blanke et al. (2008)

- New results on $B_s \to \mu^+\mu^-$ begin cutting into the interesting parameter space
- Expected effects in B_s mixing are compatible with new LHCb range

Theoretical predictions: BMSSM

A generalized SUSY model with additional CP phases in the Higgs sector from higher-dimensional operators can give rise to interesting effects in the B_s system:





Altmannshofer, Carena, Gori, de la Puente (2011)
Alejandro de la Puente @ SUSY11 (SUN);
Wolfgang Altmannshofer @ SUSY11 (THU)

- New upper bound on $B_s \to \mu^+\mu^-$ implies an interesting upper limit on the magnitude of the New Physics contributions to CP violation in B_d and B_s mixing (red points)

Minimal Flavor Violation:

Renormalization Group Invariants

They allow a direct connection between low and high energy quantities.

Interestingly enough, there are 14 RGIs in the MSSM

Invariant	Symmetry	Dependence on Soft Masses
$D_{B_{13}}$	$B_1 - B_3$	$2(m^2_{\tilde{Q}_1} - m^2_{\tilde{Q}_3}) - m^2_{\tilde{u}_1} + m^2_{\tilde{u}_3} - m^2_{\tilde{d}_1} + m^2_{\tilde{d}_3}$
$D_{L_{13}}$	$L_1 - L_3$	$2(m^2_{\tilde{L}_1} - m^2_{\tilde{L}_3}) - m^2_{\tilde{e}_1} + m^2_{\tilde{e}_3}$
D_{χ_1}	χ_1	$3(3m^2_{\tilde{d}_1} - 2(m^2_{\tilde{Q}_1} - m^2_{\tilde{L}_1}) - m^2_{\tilde{u}_1}) - m^2_{\tilde{e}_1}$
$D_{Y_{13H}}$	$Y_1 - \frac{10}{13} Y_{3H}$	$m^2_{\tilde{Q}_1} - 2m^2_{\tilde{u}_1} + m^2_{\tilde{d}_1} - m^2_{\tilde{L}_1} + m^2_{\tilde{e}_1} - \frac{10}{13}$ (1<->3+H)
D_Z	Z	$3(m^2_{\tilde{d}_3} - m^2_{\tilde{d}_1}) + 2(m^2_{\tilde{L}_3} - m^2_{H_d})$
$I_{Y\alpha}$	Y	$(m^2_{H_u} - m^2_{H_d} + \sum_{gen}(m^2_{\tilde{Q}} - 2m^2_{\tilde{u}} + m^2_{\tilde{d}} - m^2_{\tilde{L}} + m^2_{\tilde{e}}))/g_1^2$
I_{B_r}		M_r/g_r^2
I_{M_1}		$M_1^2 - \frac{33}{8}(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$
I_{M_2}		$M_2^2 + \frac{1}{24}(9(m^2_{\tilde{d}_1} - m^2_{\tilde{u}_1}) + 16m^2_{\tilde{L}_1} - m^2_{\tilde{e}_1})$
I_{M_3}		$M_3^2 - \frac{3}{16}(5m^2_{\tilde{d}_1} + m^2_{\tilde{u}_1} - m^2_{\tilde{e}_1})$
I_{g_2}		$1/g_1^2 - 33/(5g_2^2)$
I_{g_3}		$1/g_1^2 + 33/(15g_3^2)$

M. Carena, PD, N. Shah, C. Wagner 2010

Applications of RGI's

RGI sum rules have been considered by many authors :

Martin & Ramond 1993; Kawamura, Kobayashi, Kubo 1997; Kazakov 1997; Hisano & Shifman 1997 Jack, Jones, Pickering 1997; Arkani-Hamed, Giudice, Luty, Rattazzi 1997; Carena, Huiti, Kobayashi 2000 Kobayashi & Yoshioka 2000; Ananthanarayan & Pandita 2005; Demir 2005; Kane, Kumar, Morrissey, Toharia 2007; Meade, Seiberg, Shih 2009; Balazs, Li, Nanopoulos, Wang 2010; etc...

- For most general flavor independent models, establish two sum rules and a one to one relationship between RGIs and parameters of the model, apart from the messenger scale

- For minimal models, several rum rules are established, that lead to spectrum predictions from a limited number of observables.

M. Carena, P. Draper, N. Shah, C.W. '10 & '11

Generic Flavor Blind Models

$D_{B_{13}} = 0$ and $D_{L_{13}} = 0$ → direct tests of the flavor-blind hypothesis

★ 5 sfermion masses, 3 gauginos, 2 Higgs mass parameters, 3 gauge couplings

13 d.o.f at the scale M and 12 RGIs

==> can reconstruct everything as an algebraic function of one unknown M

all couplings and soft masses at scale M

$$M_1 = g_1^2 I_{B_1}, \qquad M_2 = g_2^2 I_{B_2}, \qquad M_3 = g_3^2 I_{B_3}$$

$$m_{\tilde{L}}^2 = -\frac{1}{440}(26D_{Y_{13H}} + 11D_{\chi_1} + 20((g_1^4 I_{B_1}^2 + 33g_2^4 I_{B_2}^2) - (I_{M_1} + 33I_{M_2}) + g_1^2 I_{Y\alpha})),$$

$$m_{H_d}^2 = m_{\tilde{L}}^2 - \frac{1}{2}D_Z, \quad m_{H_u}^2 = m_{\tilde{L}}^2 - \frac{1}{2}D_Z - \frac{13}{11}D_{Y_{13H}} + \frac{g_1^2}{11}I_{Y\alpha}, \quad m_{\tilde{e}}^2 = \frac{1}{220}(26D_{Y_{13H}} + 11D_{\chi_1} - 20(2(g_1^4 I_{B_1}^2 - I_{M_1}) - g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{u}}^2 = -\frac{1}{990}(78D_{Y_{13H}} + 33D_{\chi_1} + 20(4((g_1^4 I_{B_1}^2 - 11g_3^4 I_{B_3}^2) - (I_{M_1} - 11I_{M_3})) + 3g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{d}}^2 = \frac{1}{1980}(78D_{Y_{13H}} + 33D_{\chi_1} - 20(2((g_1^4 I_{B_1}^2 - 44g_3^4 I_{B_3}^2) - (I_{M_1} - 44I_{M_3})) - 3g_1^2 I_{Y\alpha})),$$

$$m_{\tilde{Q}_1}^2 = \frac{1}{3960}(78D_{Y_{13H}} - 627D_{\chi_1} - 20((g_1^4 I_{B_1}^2 + 297g_2^4 I_{B_2}^2 - 176g_3^4 I_{B_3}^2) - (I_{M_1} + 297I_{M_2} - 176I_{M_3}) - 3g_1^2 I_{Y\alpha})).$$

$g_a(t_M) = [g_a(t_0)^{-2} - B_a(t_M - t_0)/8\pi^2]^{-\frac{1}{2}}$ → only t_M remains unknown

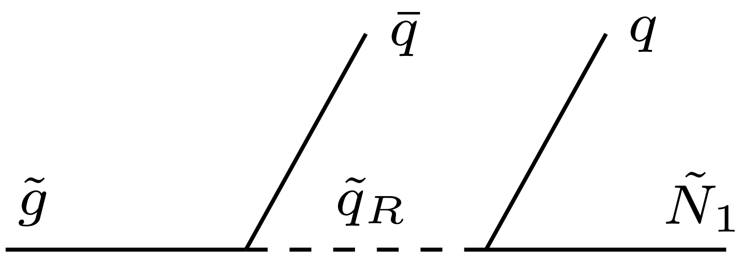
Bound all parameters by requiring 5 < log(M/GeV) <16 => extra uncertainty

Supersymmetry Searches at Colliders

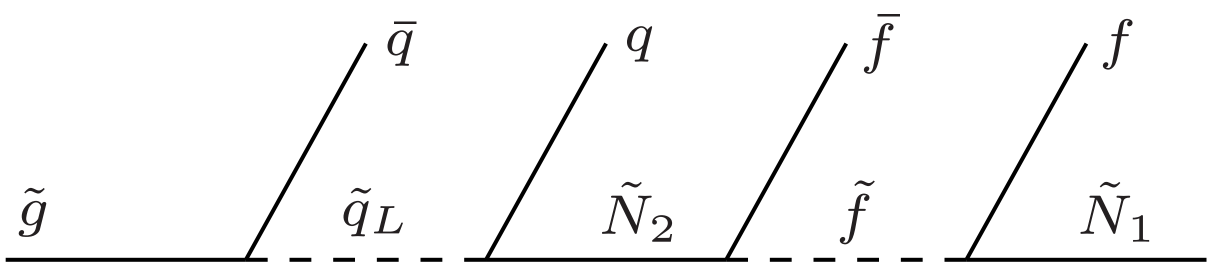
Gluino Decays:

The gluino can only decay through squarks, either on-shell (if allowed) or virtual.

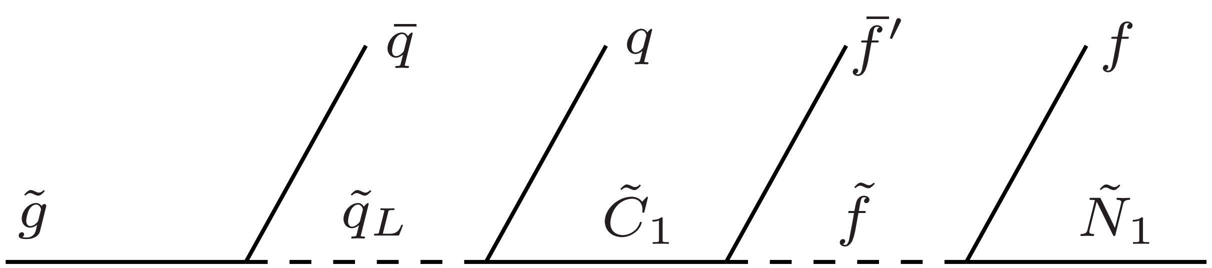
For example:



$jj + \not{E}$ or $t\bar{t} + \not{E}$



$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or $jj\ell^+\ell^- + \not{E}$



$jjjj + \not{E}$ or $t\bar{t}jj + \not{E}$ or $jj\ell^{\pm} + \not{E}$

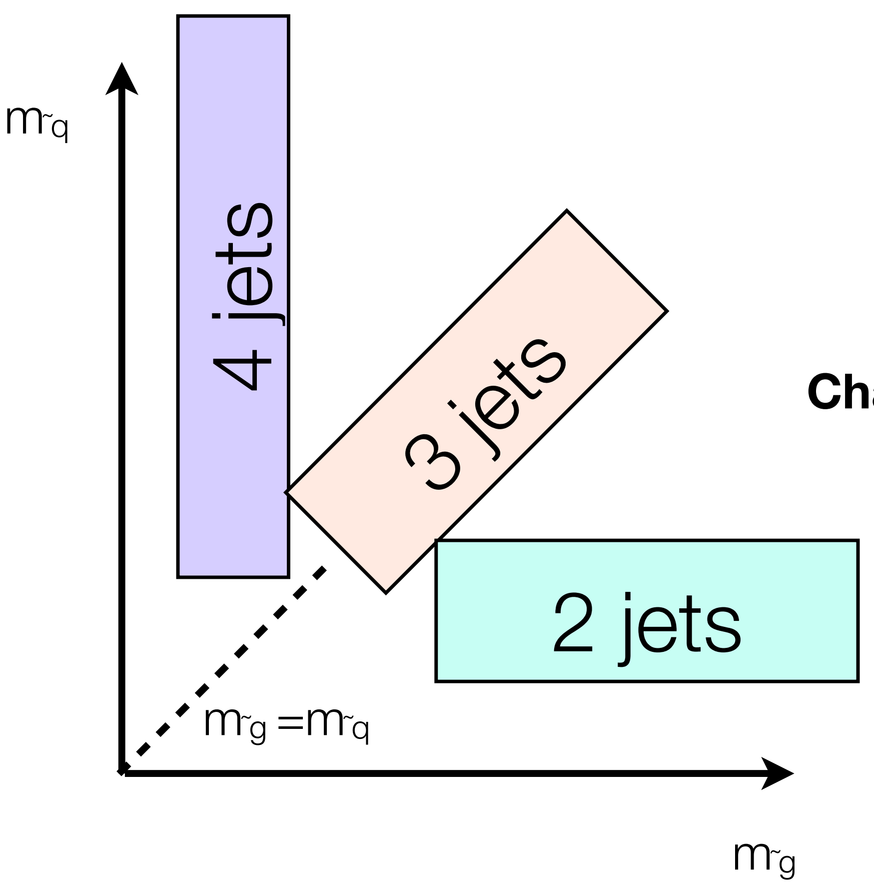
If $m_{\tilde{t}_1} \ll$ other squark masses, top quarks can appear in these decays.

The possible signatures of gluinos and squarks are numerous and complicated **due to cascade decays**

Event selection

Nojiri

- Depending on the SUSY mass hierarchy, different production processes favoured ($\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$)
  - Signal regions optimised to maximise sensitivity to different production processes



	Signal Region	$\geq$ 2 jets	$\geq$ 3 jets	$\geq$ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

Heavy Flavor SUSY searches

What are these searches?

(searches useful for 1/fb to 15/fb)

J. Wacker

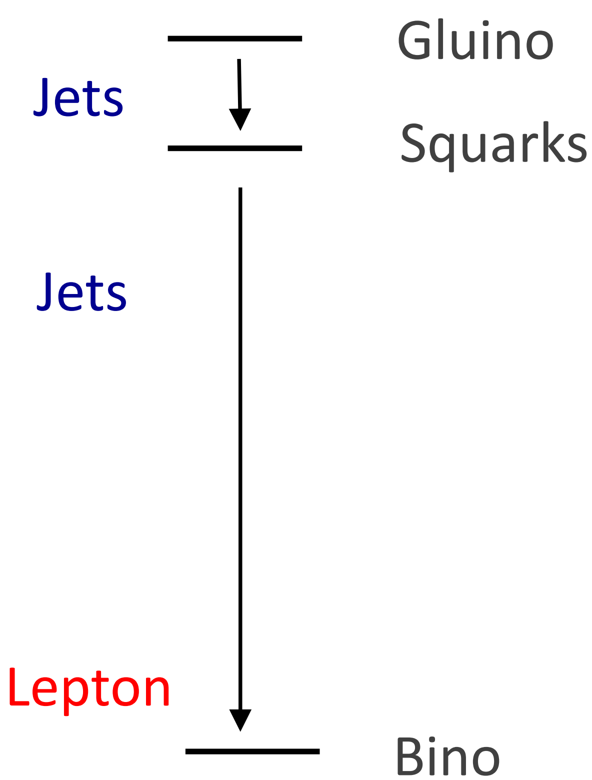
	Search Region	N_j	N_ℓ	N_{bjet}	$\not{E}_T$	H_T
High HT	1	4^+	0	0	300	1000
High MET	2	4^+	0	0	400	500
1 b Low multiplicity	3	2^+	0	1^+	400	400
1 b High HT	4	4^+	0	1^+	300	800
1 b High MET	5	4^+	0	1^+	400	500
2 b High MET	6	3^+	0	2^+	250	400
3 b High MET	7	3^+	0	3^+	250	600
3 b Low MET	8	4^+	0	3^+	150	300
b SSDL	9	2^+	SSDL	1^+	0	200

2 Normal Light Flavor

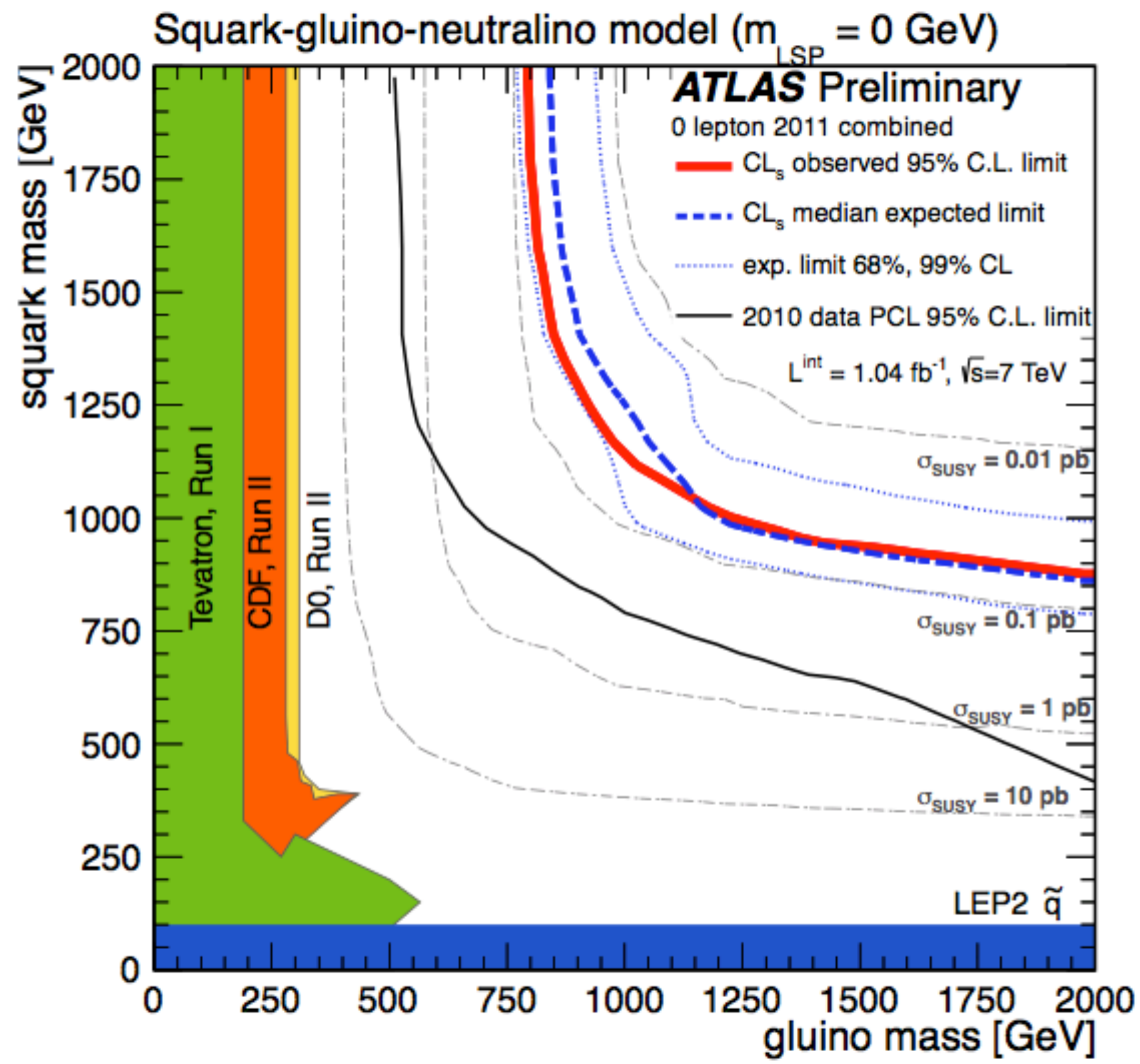
4 Normal Heavy Flavor

3 Low BG Heavy Flavor

Jets + MET Signature

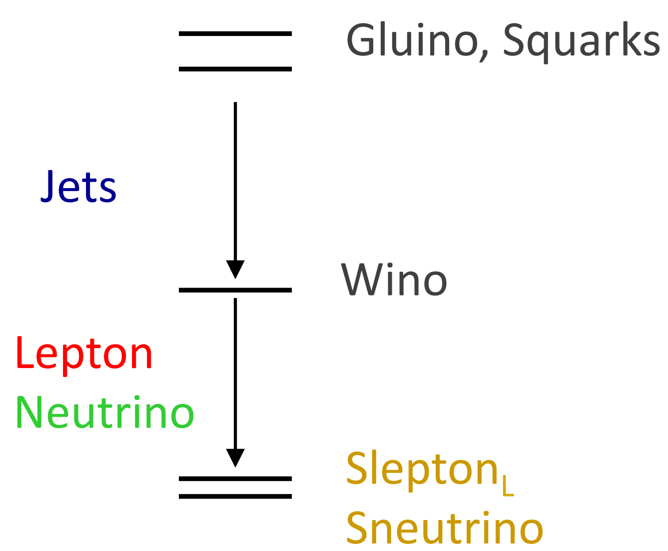


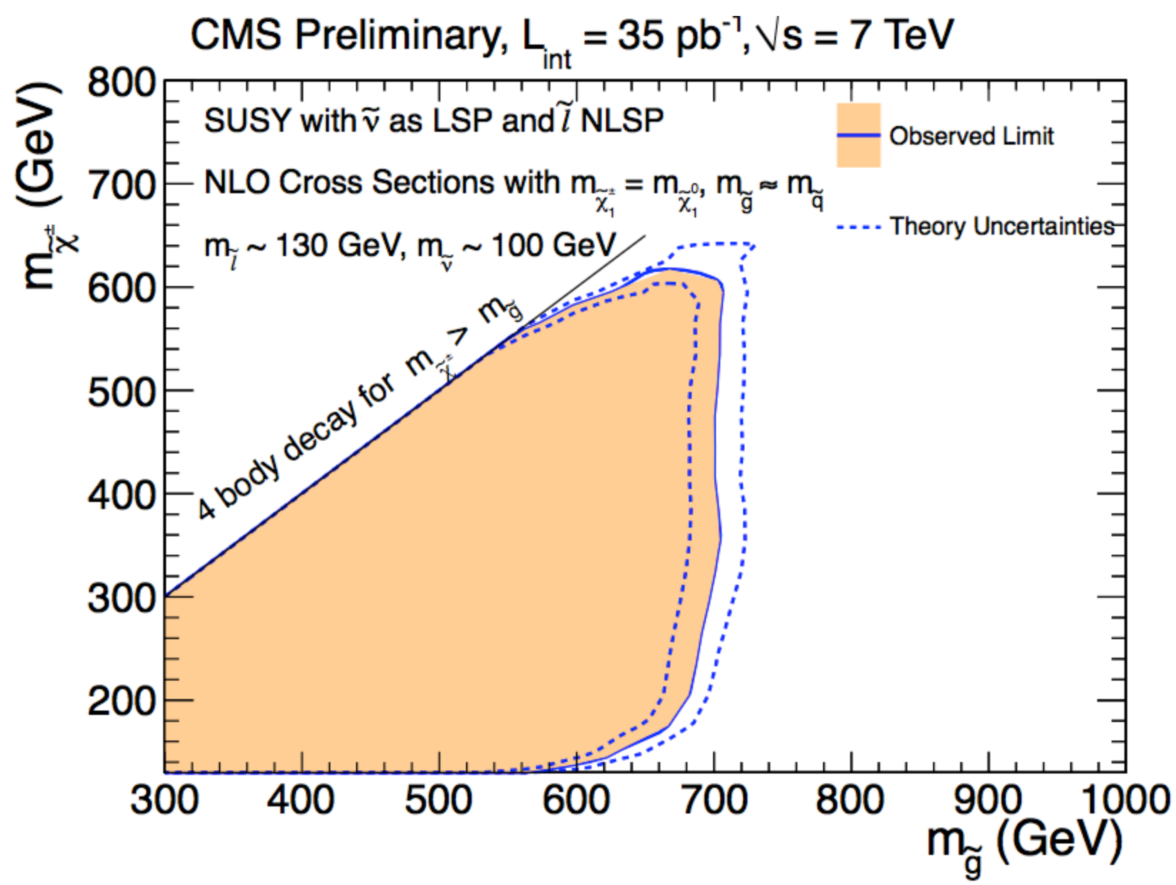
$N_{lepton} = 0$



S.Thomas

Same Sign Leptons + Jets + MET Signature





S. Thomas

Direct Searches for Super-Symmetry

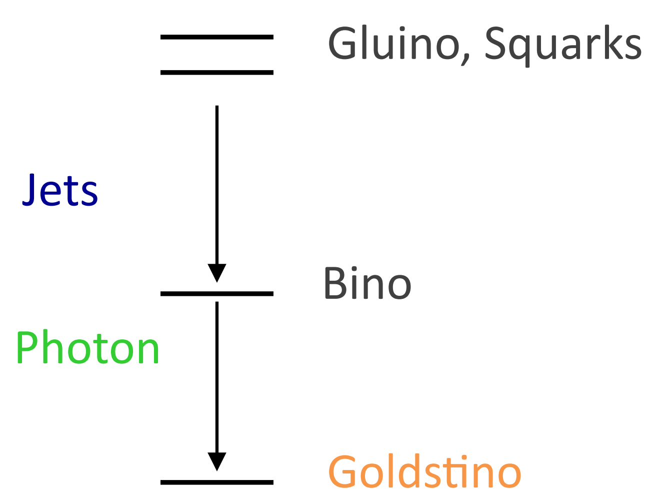
Super-Partners + Super-Interactions

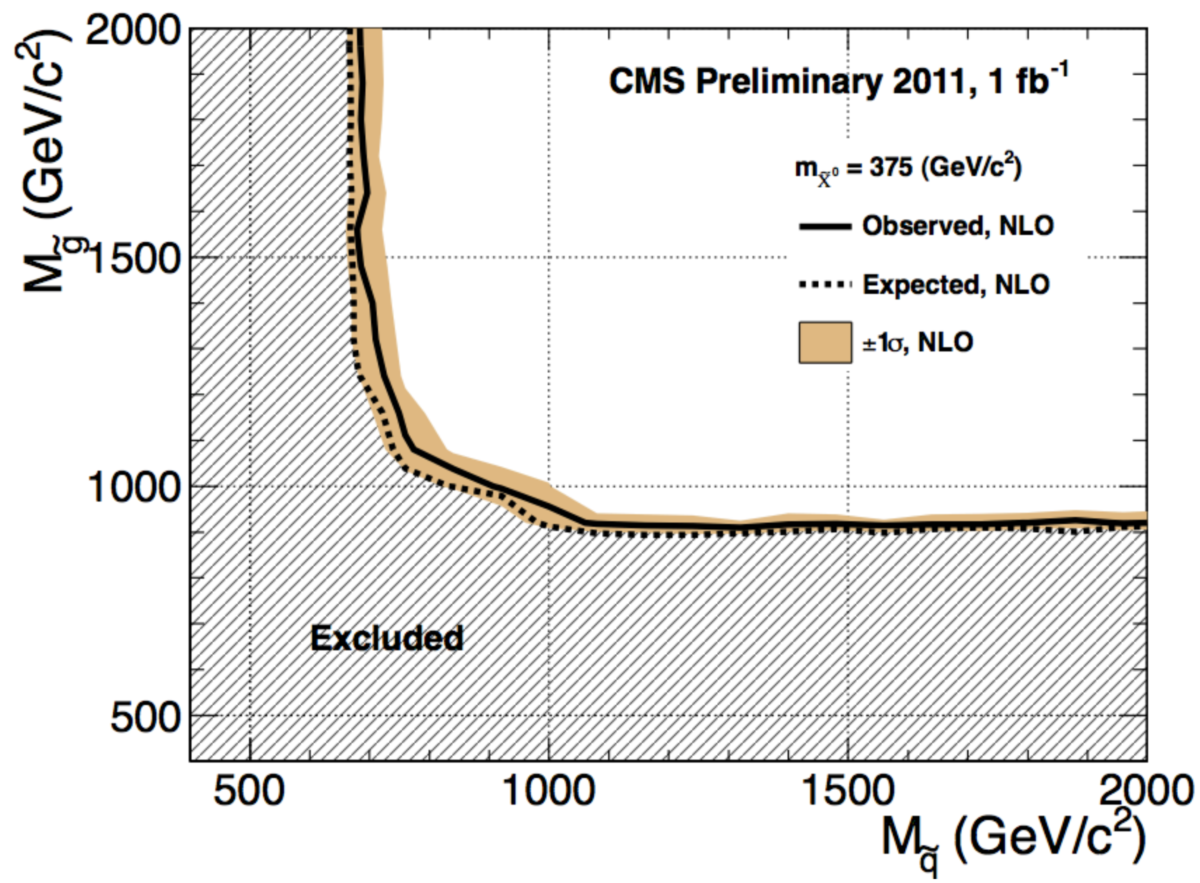
+ Goldstino	
+ New Interactions	(~~R-Symmetry~~, B or L Conserved)
+ Global Symmetry Violation	(Lepton Flavor, ...)
+ New Global Symmetries	($U(1)_R$, ...)
+ New Matter fields	(Vector Like, Dark Matter, ...)
+ New Higgs fields	(Singlets, ...)
+ New Gauge Interactions	(Abelian, Non-Abelian)
+ ...	

S. Thomas

Di-Photon + Jets + MET Signature

Prompt Decay





S. Thomas

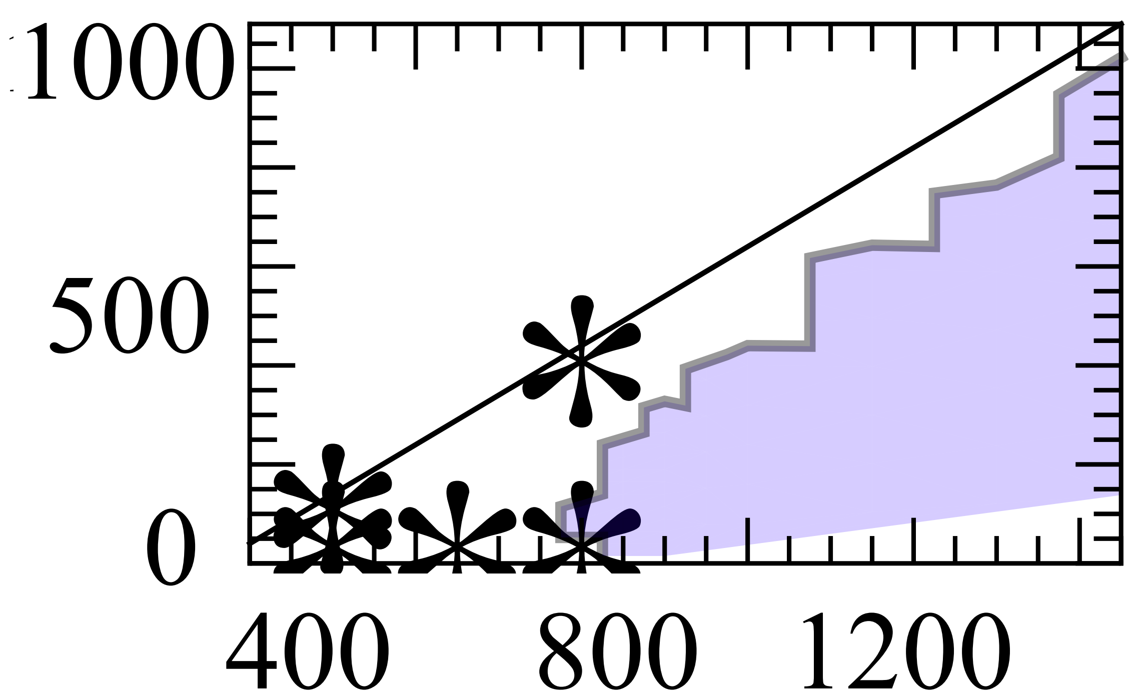
4 Tops + MET

J. Wacker

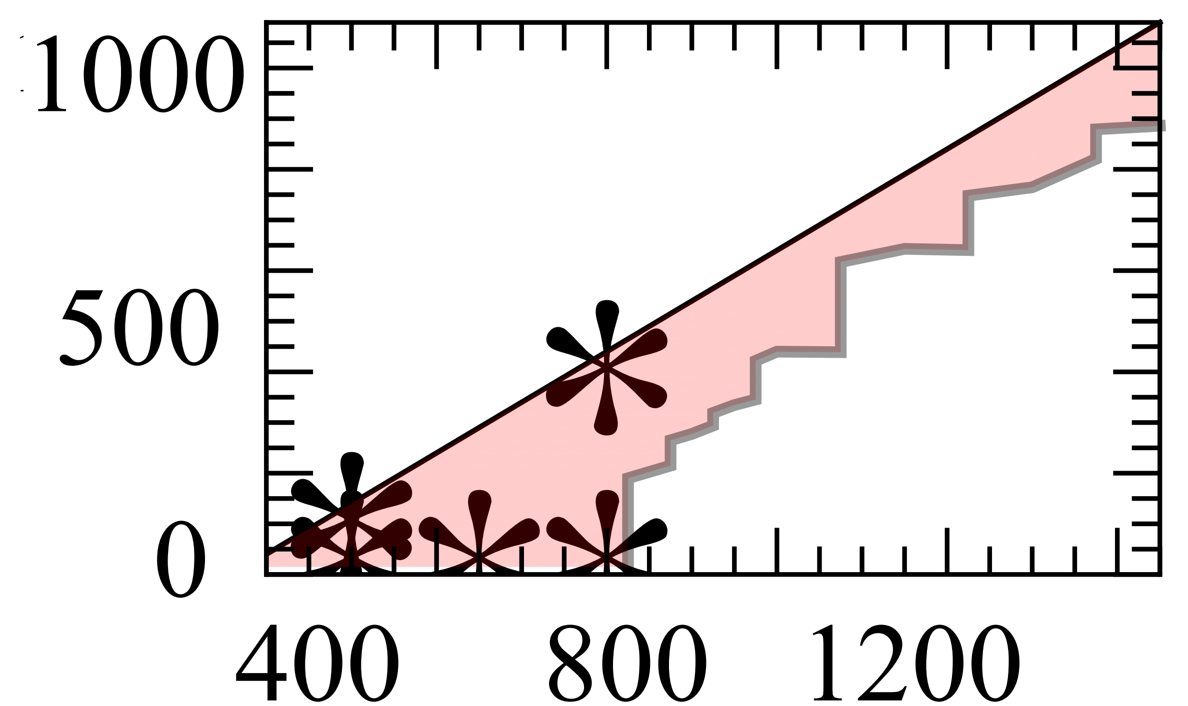
$$\tilde{g}\tilde{g} \rightarrow (t\bar{t}\chi^0)(t\bar{t}\chi^0)$$

2 Search Regions Cover Everything at 1 fb^{-1}

4 jets, 1 bjet, MET>400



2 jets, 1 bjet, SSDL

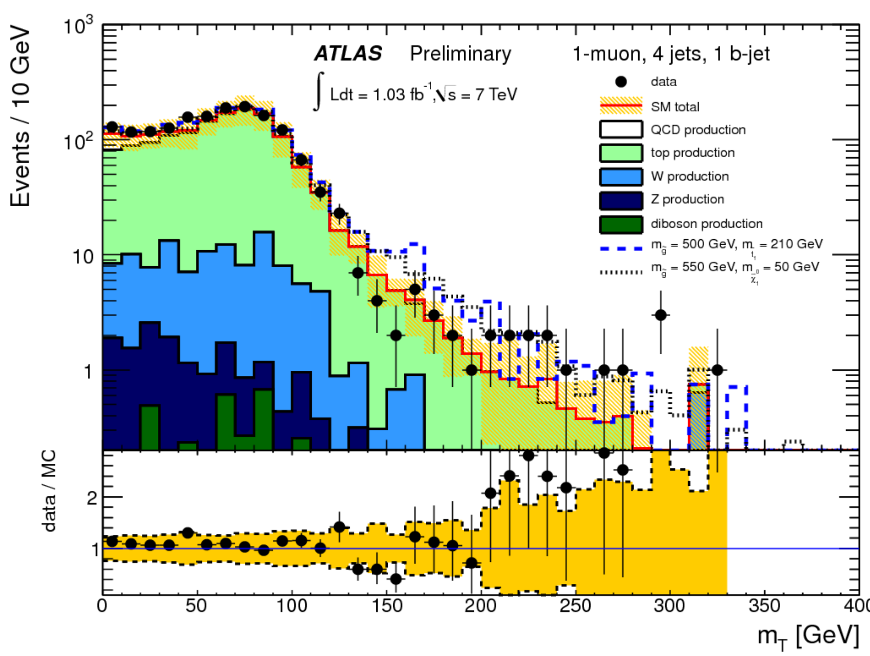


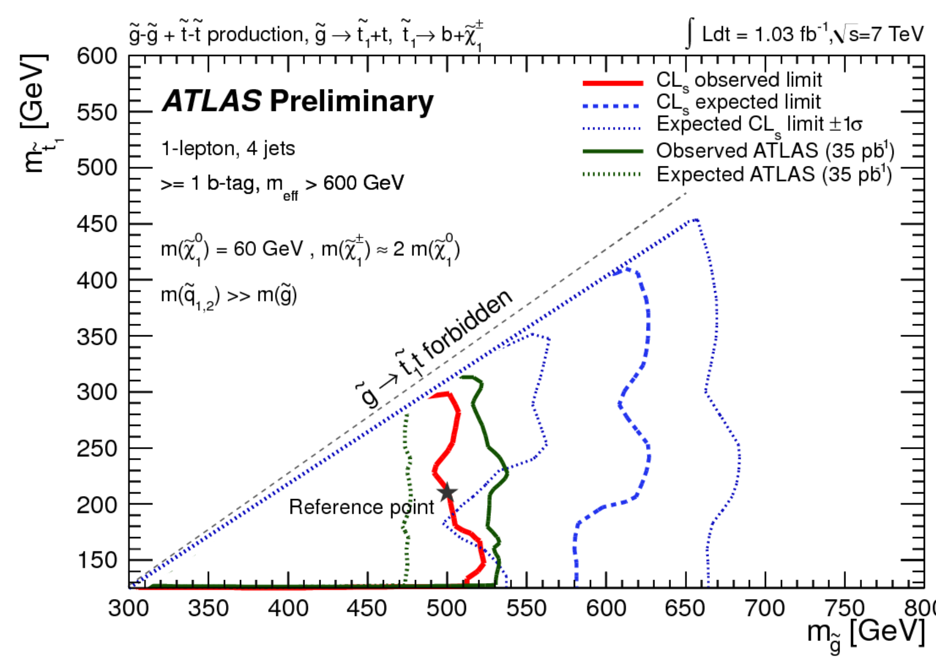
One Lepton + b-jets + Missing E_T

Update LP2011

- 3rd generation is special: has to be light to stabilize the Higgs
- selection similar to one lepton + 4 jets + missing E_T plus 1 b-tags
- signal region defined by missing E_T > 80 GeV, m_T> 100 GeV and m_{eff} > 600 GeV

Phenomenological MSSM:
BR($g \rightarrow t_1 t \rightarrow tb\chi^{\pm}_1$) = 100%





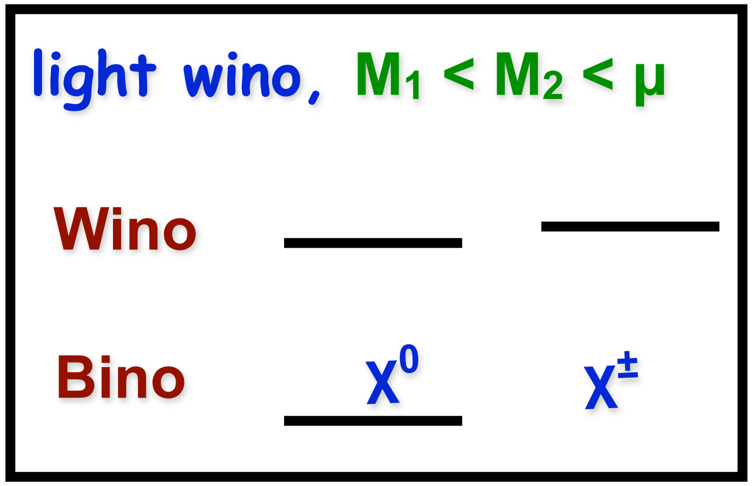
Relatively light stops are naturally there, they can raise sufficiently the Higgs mass and are not ruled out by current data !

They should be a priority in LHC searches (in all possible stop decay channels)

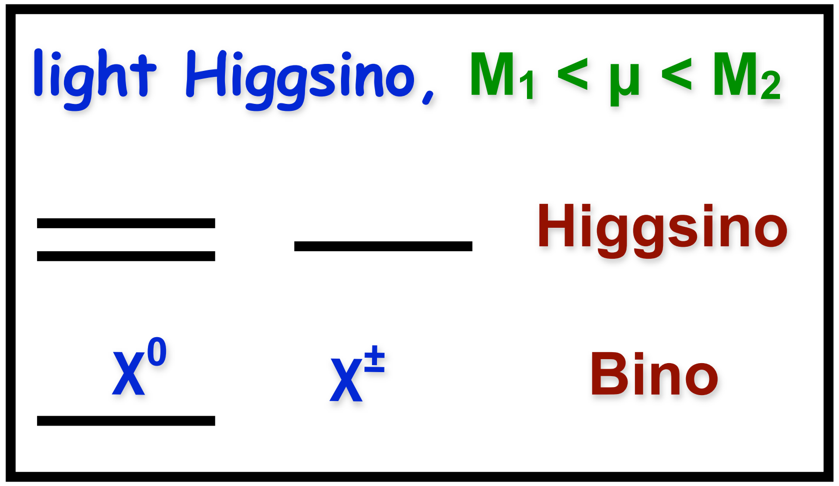
Exploring LHC reach for the electroweak sector of MSSM
neutralinos, charginos and sleptons.

Han, Padhi and Su

- Colored superparticle
  - no indication from current LHC search, mass limit of about 1 TeV.
  - what if colored particles are so heavy, out of the reach of LHC?
- EW interacting particles
  - suffer from small electroweak direct production
  - current SUSY search strategy is not sensitive to light EW interacting particles (large H_T cuts reduce the signal efficiency)



sleptons
- decouple
- light, off-shell
- light, on-shell

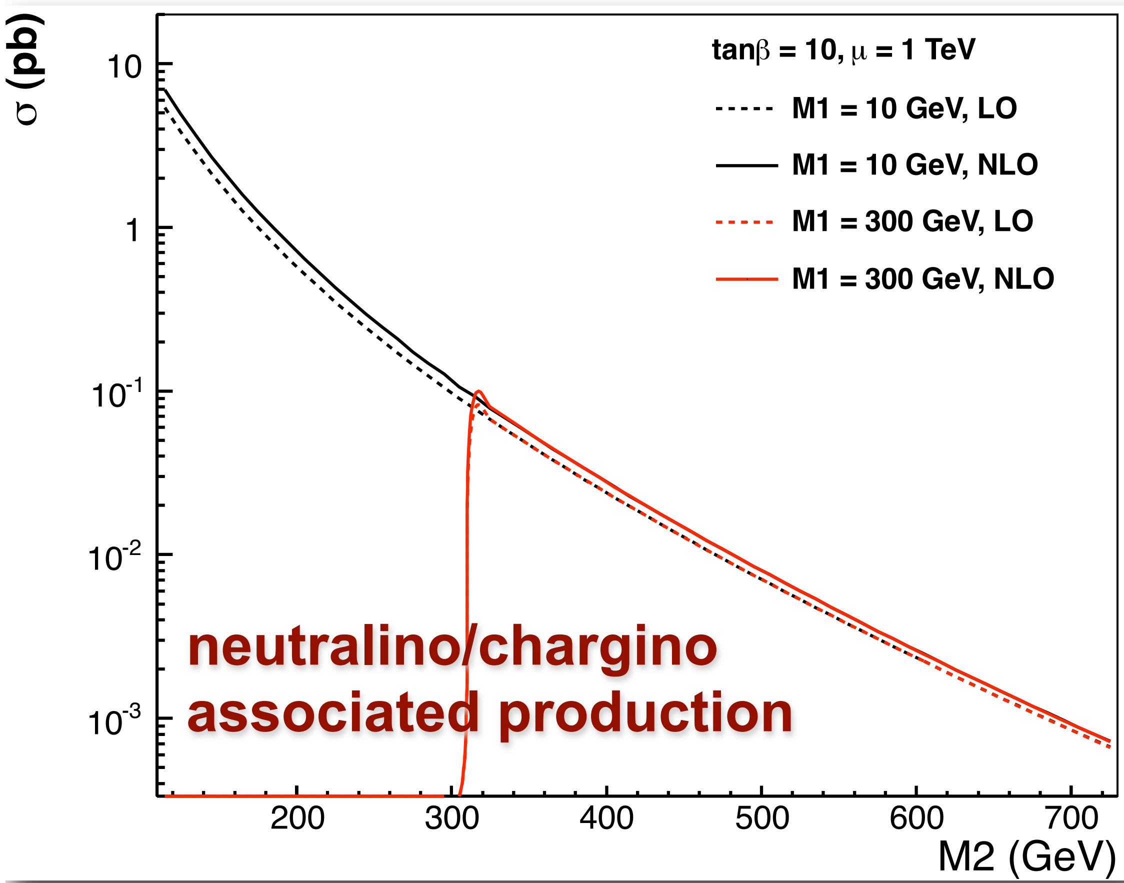


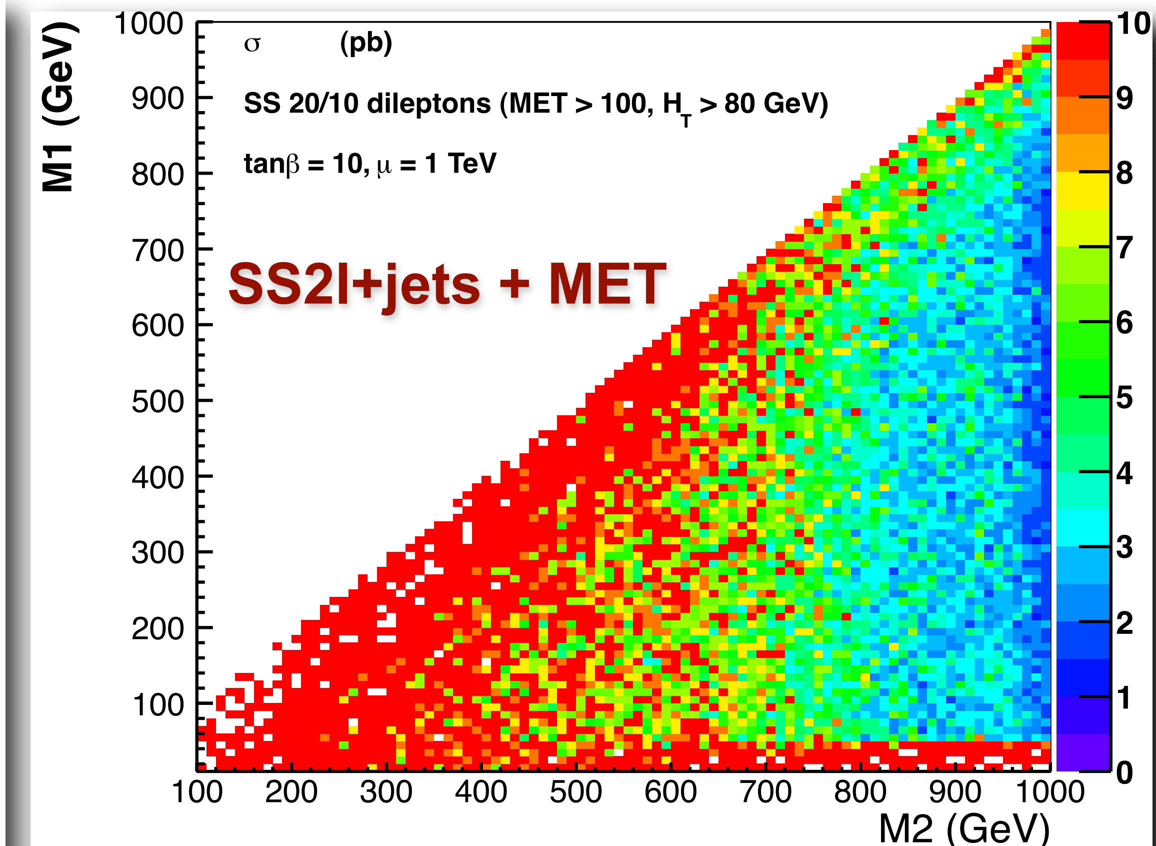
LHC Reaches

Collider signatures

- jets + MET
- 1l + jets + MET
- OS2l + jets + MET
- SS2l + jets + MET

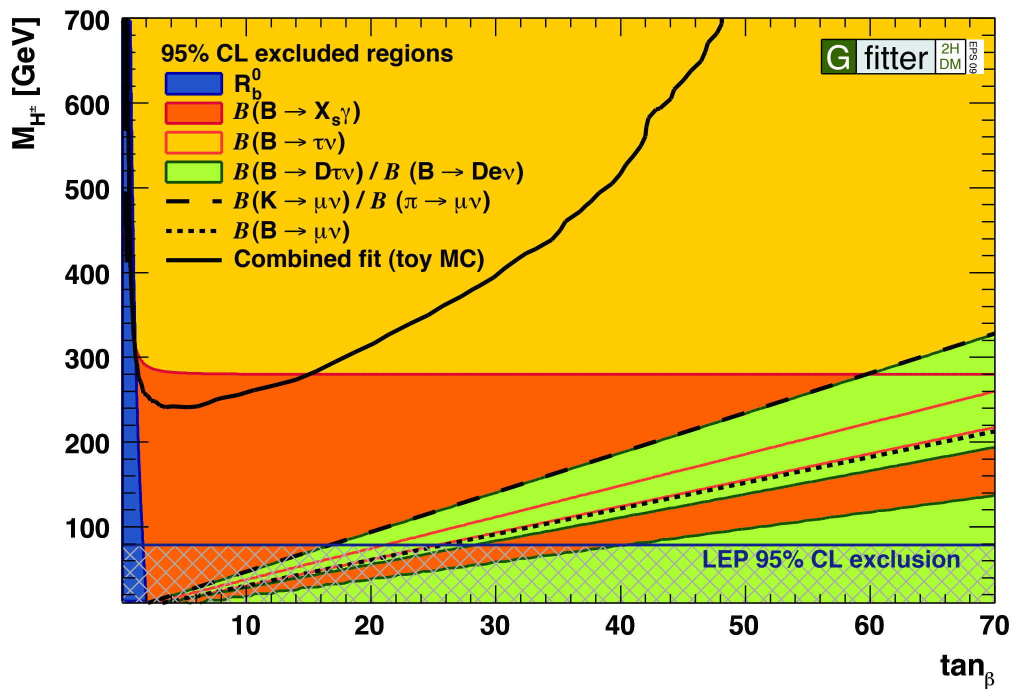
- 0.98 fb^{-1} has no reach
- with more data (even just 10fb^{-1}), could have reach beyond LEP limit.

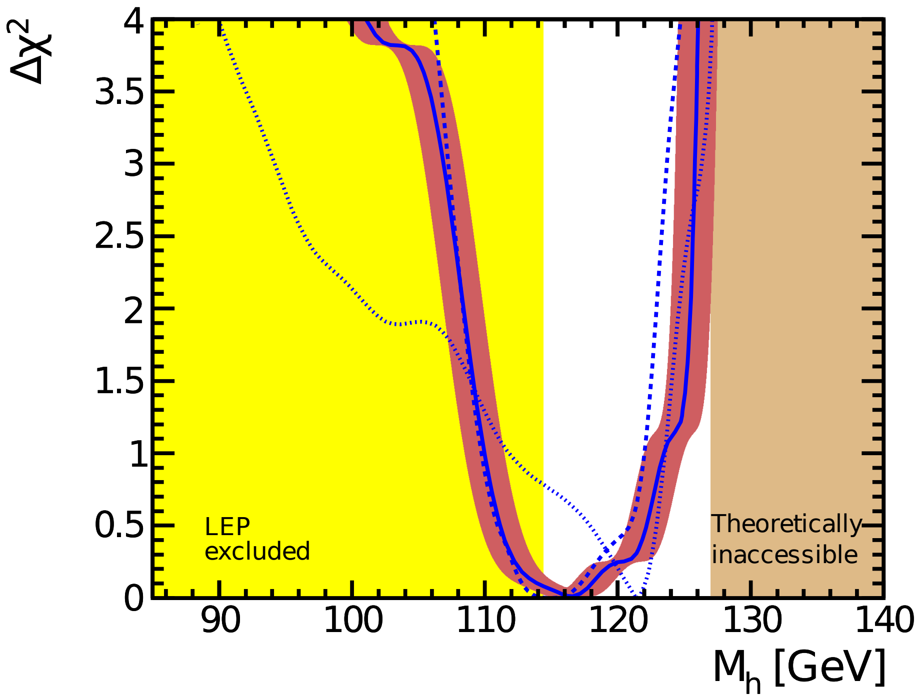




Higgs Physics

Precision electroweak constraints can also be applied to the 2HDM and the MSSM.



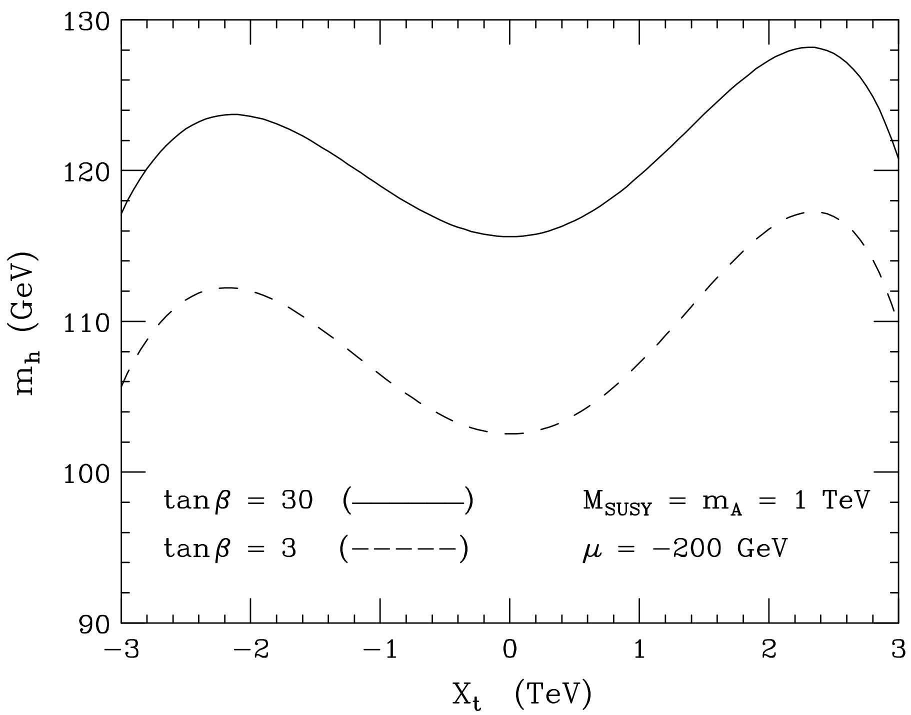


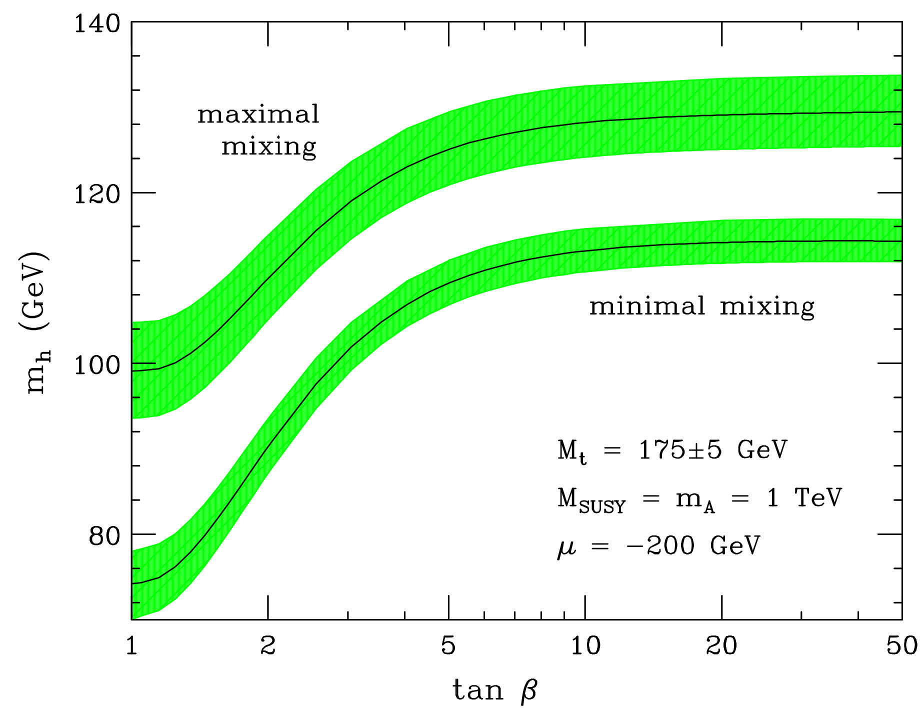
The left-hand plot provides constraints on the Type-II 2HDM.

The right-hand plot [taken from O. Buchmüller et al., Eur. Phys. J. **C71**, 1634 (2011)] shows Higgs mass constraints in the NUHM1 extension of the CMSSM (with non-universal Higgs mass parameters).

Best fit in the CMSSM in the LEP allowed region.
Regions excluded by LHC tend to produce light Higgs, at or below the LEP bound !

The state-of-the-art computation includes the full one-loop result, all the significant two-loop contributions, some of the leading three-loop terms, and renormalization-group improvements. The final conclusion is that $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].





H. Haber

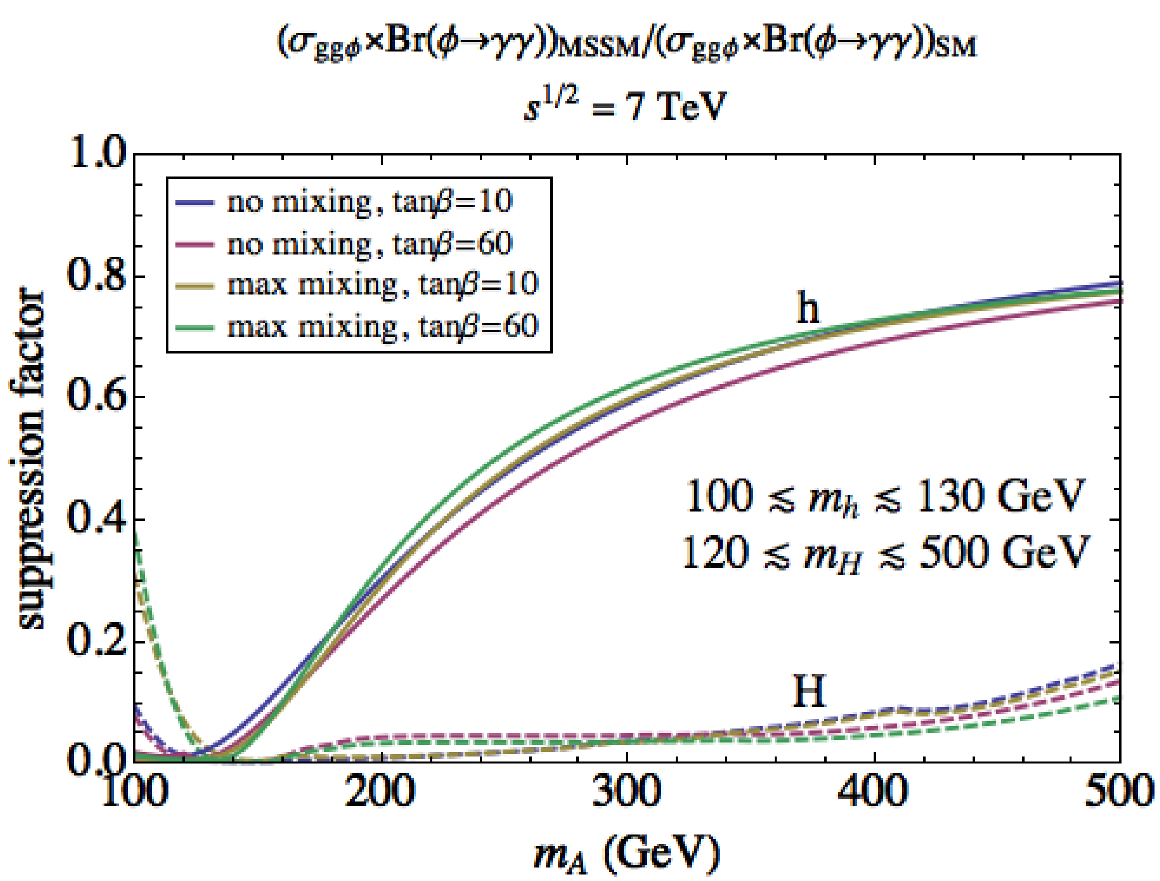
Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.

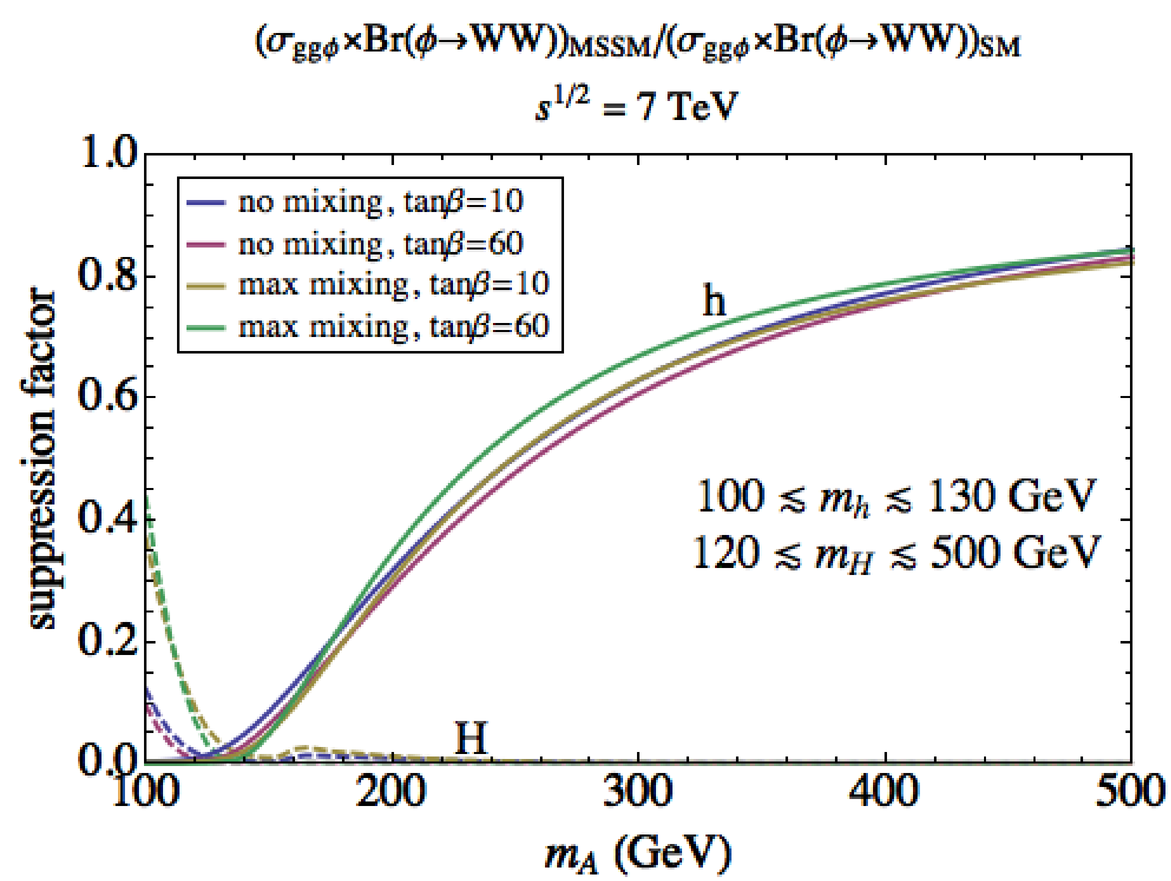
Minimal models, like the MSSM tend to lead to small Xt and relatively large CP-odd masses. Both stops could be as light as a few hundred GeV if mixing parameter Xt is large.

MSSM Higgs Searches at the LHC

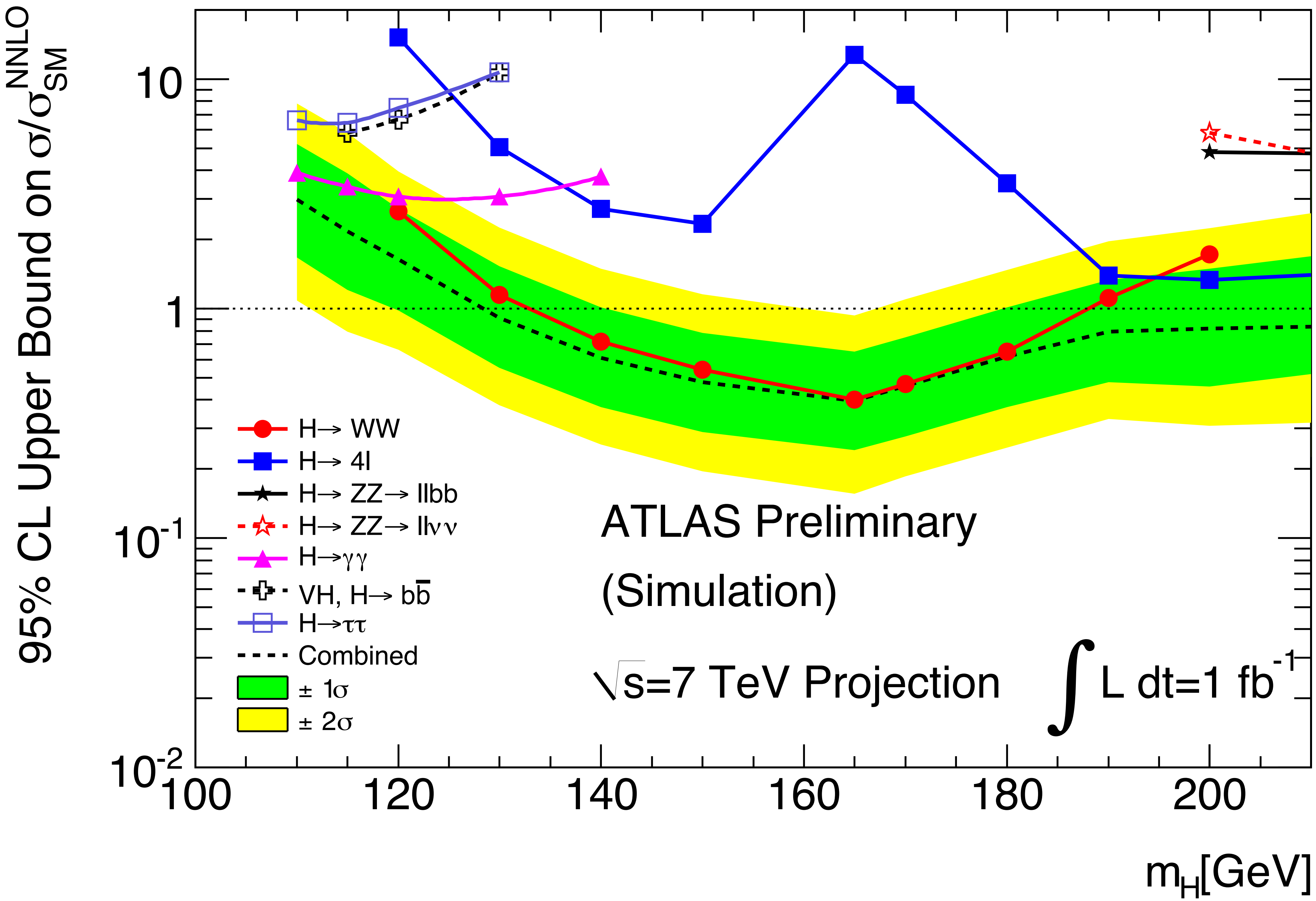
P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

- In the MSSM, one of the Higgs bosons has standard model like couplings to the top and gauge bosons
- Relevant SM-like channels of production and/or decay are induced by loops, which are affected by new physics (mainly stops). We shall assume all relevant supersymmetric particles to be heavy, with masses of order 1 TeV.
- Moreover, the dominant width of Higgs decay into bottom quarks is enhanced due to mixing with non-standard Higgs bosons. Top Yukawa tend to be somewhat reduced by same effect. This affects the main production and decay channels.





$$\text{Expected Significance}(\sigma) = 2/R_{\text{expected}}$$

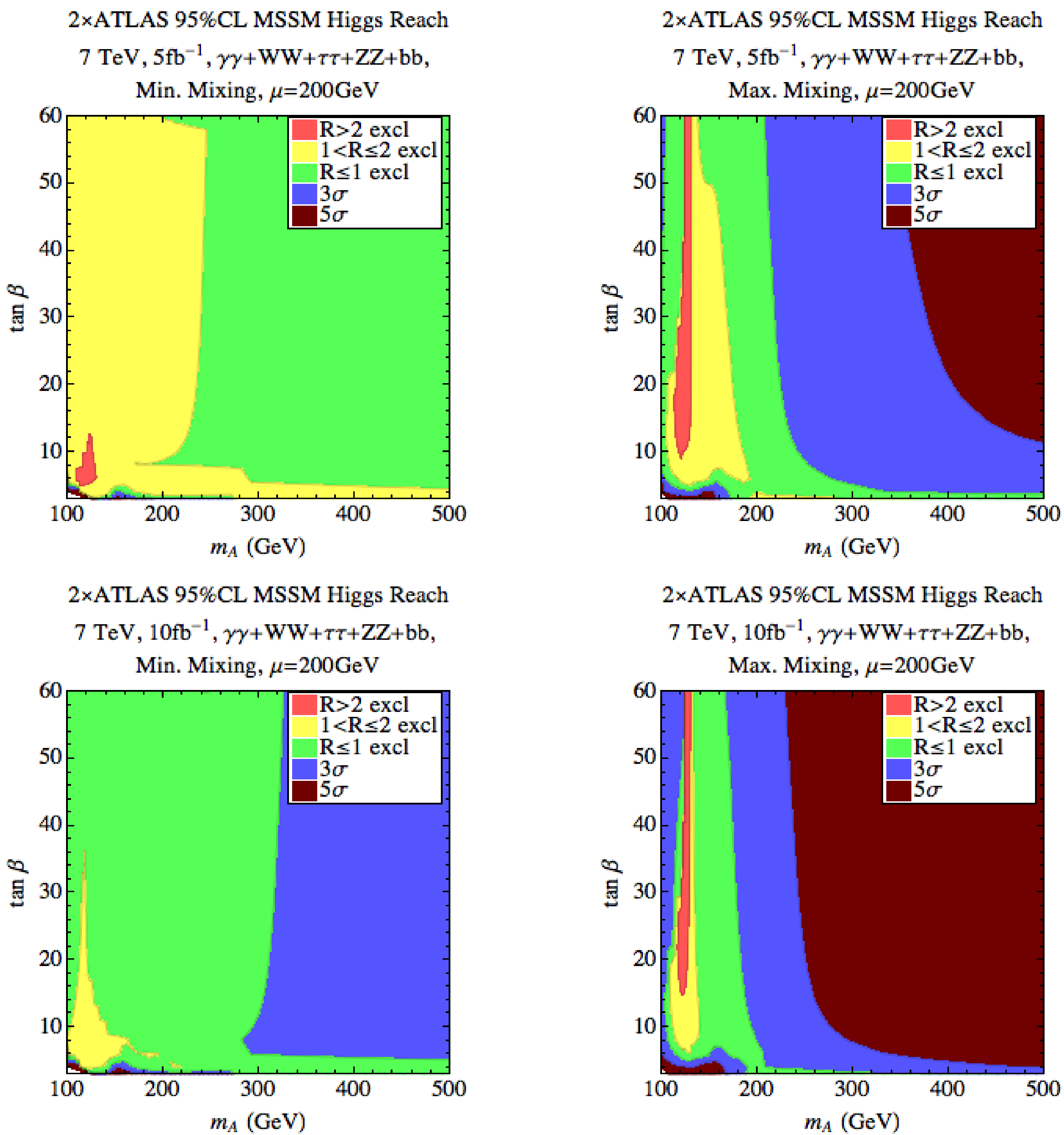


With 5 inverse fb (about the end of this year) each experiment expects to be able to probe a SM Higgs in the whole range above 115 GeV and combination of ATLAS and CMS could lead to evidence on this mass range.

7 TeV LHC MSSM Higgs Reach

P. Draper, T. Liu, C. Wagner, **Phys.Rev.D81:015014,2010**; M. Carena, P. Draper, T. Liu, C. Wagner, arXiv:1107.4354

$m_h \simeq 115\text{GeV}$ $m_h \simeq 130$ GeV



Suppression of

$$BR(h \to \gamma\gamma)$$

leads to reduced reach at low values of the CP-odd Higgs mass

$$\text{Significance}(\sigma) = 2/R$$

At sufficiently large luminosity

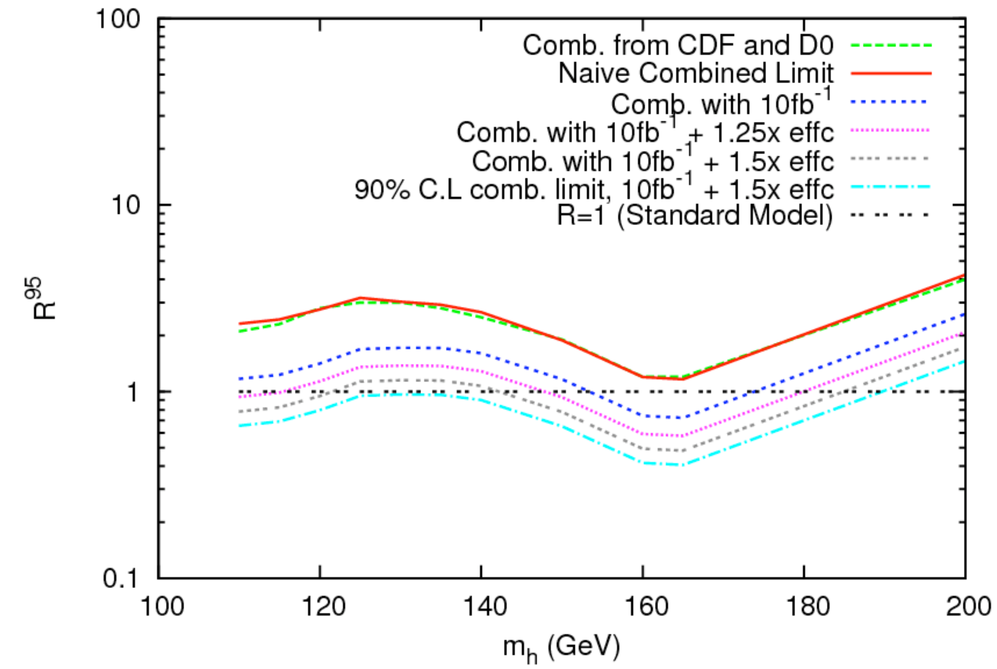
$$Vh, h \to bb$$

$$\text{WBF}, h \to \tau\tau$$

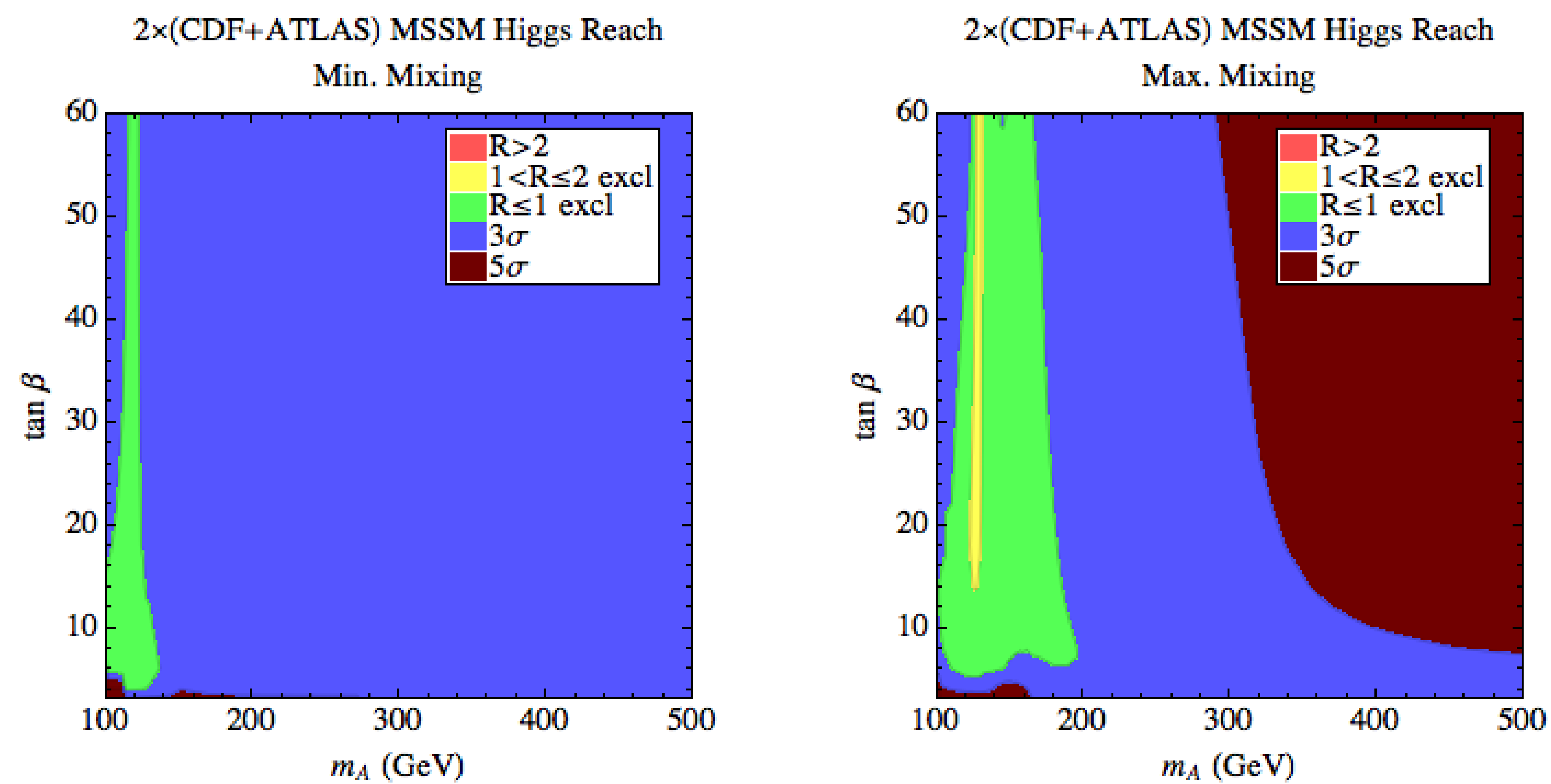
are helpful in partially reducing the reach suppression

The LHC sensitivity is somewhat complementary to that of the Tevatron, which becomes more sensitive for low Higgs masses.

Combination of data from experiments at the end of 2011 may be useful to find evidence for Higgs at an early stage.



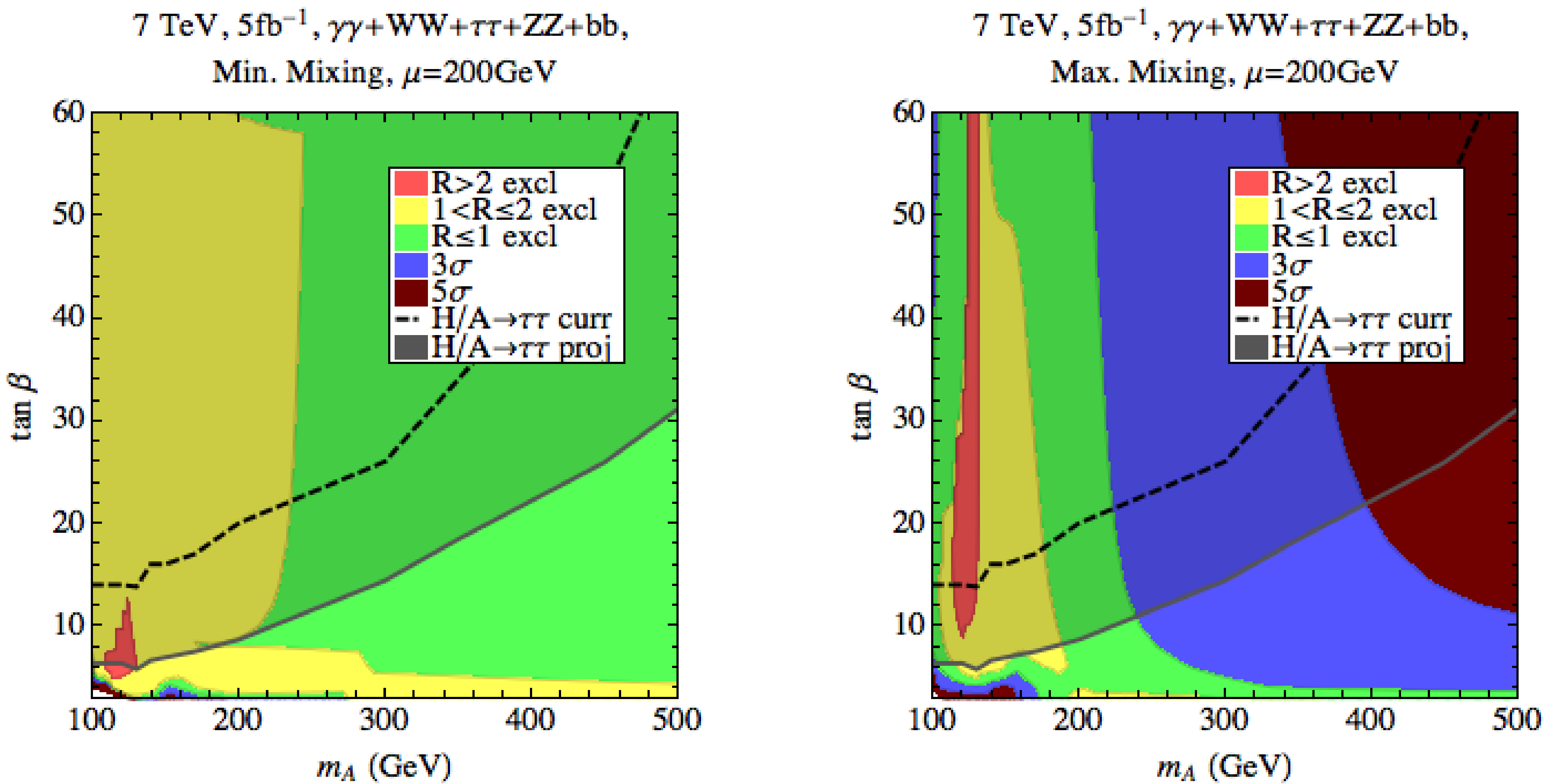
P. Draper, T. Liu and C. Wagner'09



Combination of 5 inverse fb LHC with 10 inverse fb Tevatron data :
Evidence of SM-like Higgs presence in almost all parameter space

M. Carena, P. Draper, T. Liu, C.W.'11

Complementarity with LHC non-standard Higgs searches



M. Carena, P. Draper, T. Liu, C.W.' 11

Non-standard Higgs searches allow to probe part of the parameter space for which standard reach is suppressed

Search for SM-like Higgs Boson from SUSY Particle Decays

Parameter space consistent with Neutralino Relic Density: Heavy Sleptons

Look for boosted SM-like Higgs bosons, decaying to bottom quarks

Butterworth, Davison, Rubin, Salam'08

Higgs from heavy sparticle decays tend to be boosted

Kribs, Martin, Roy, Spannowsky'10

Countours of proper relic density

$\text{Green}: \tan\beta = 50$

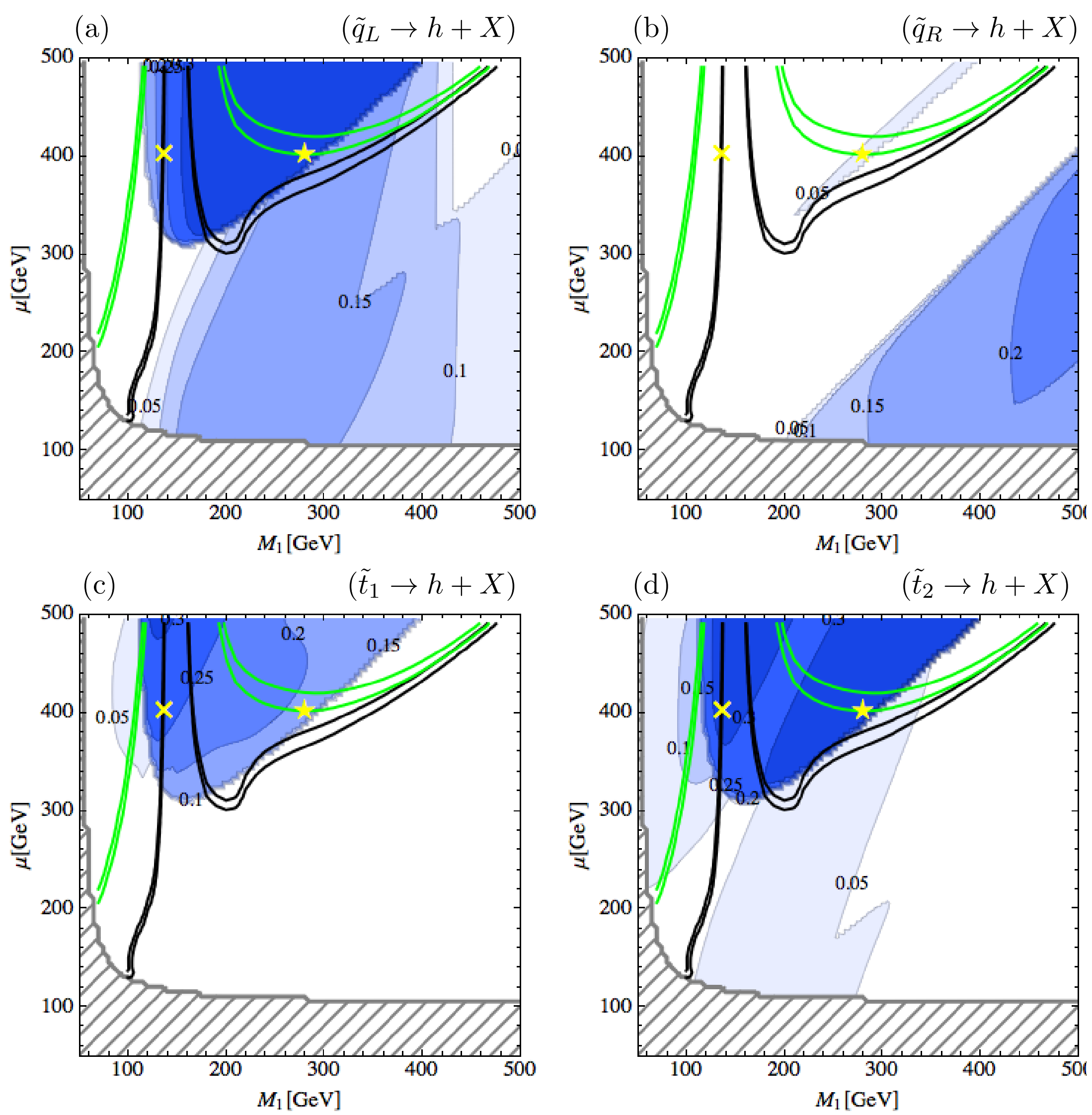
$\text{Black}: \tan\beta = 10$

$m_A = 300 \text{ GeV}$

$m_{\tilde{q}} \simeq 1 \text{ TeV}$

$M_{\tilde{g}} \simeq 6 M_1$

$M_2 = 2 M_1$



Blue regions :

Appreciable Branching Decay Fraction.

Darker means larger branching decay fraction.

X : energetic quarks, leptons and missing energy

$\text{Boosted Higgs}: p_T > 200 \text{ GeV}$

	σ[pb]	σ_{cut}[pb]	σ_h[fb]	σ_{boosted}[fb]
(I)	1.11	0.52	78	31
(II)	0.73	0.34	116	31
(III)	2.59	0.90	360	135
(IV)	1.60	0.83	231	101

Gori, Schwaller, Wagner, **Phys.Rev.D83:115022,2011**

Good prospects of observing Higgs in the 14 TeV run and, perhaps, even in the 7 TeV run.

The EFT Approach

Study extensions with ``heavy'' BMSSM degrees of freedom that couple to the Higgs sector.
(``heavy'' stands for heavier than MSSM Higgses, typically $1-2\ \mathrm{TeV}$)

- Allows relatively model-independent survey: integrate-out and describe by

$$W = \mu H_u H_d + \frac{\omega_1}{2M}(H_u H_d)^2 + \frac{\omega_2}{3M^3}(H_u H_d)^3 + \cdots$$

Brignole, Casas, Espinosa, Navarro, '03
Dine, Seiberg, Thomas, '07
Antoniadis et. al. '07 ...

Kähler potential starts at order $1/M^2$. Also F-term ~~SUSY~~.

- Matter sector more constrained, restrict here to Higgs sector (e.g. singlets, triplets, "$Z's$", W')

The EFT Approach

(Carena, Kong, EP & Zurita, 2009)

- Impose some ``sanity" checks:

  - Higher orders in 1/M expansion should be expected to be small

  Technical comment: both $1/M$ and $1/M^2$ can be phenomenologically relevant, without signalling breakdown of EFT expansion!

The EFT Approach

(Carena, Kong, EP & Zurita, 2009)

- Impose some ``sanity'' checks:

  - Higher orders in 1/M expansion should be expected to be small

  Technical comment: both $1/M$ and $1/M^2$ can be phenomenologically relevant, without signalling breakdown of EFT expansion!

$$V \supset \frac{1}{2}\lambda_1 (H_d^\dagger H_d)^2 + \frac{1}{2}\lambda_2 (H_u^\dagger H_u)^2 + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u H_d)(H_u^\dagger H_d^\dagger)$$
$$+ \left\{ \frac{1}{2}\lambda_5 (H_u H_d)^2 + \left[\lambda_6 (H_d^\dagger H_d) + \lambda_7 (H_u^\dagger H_u) \right] (H_u H_d) + \text{h.c.} \right\}$$

Special structure of MSSM potential + SUSY higher-dimension operators:

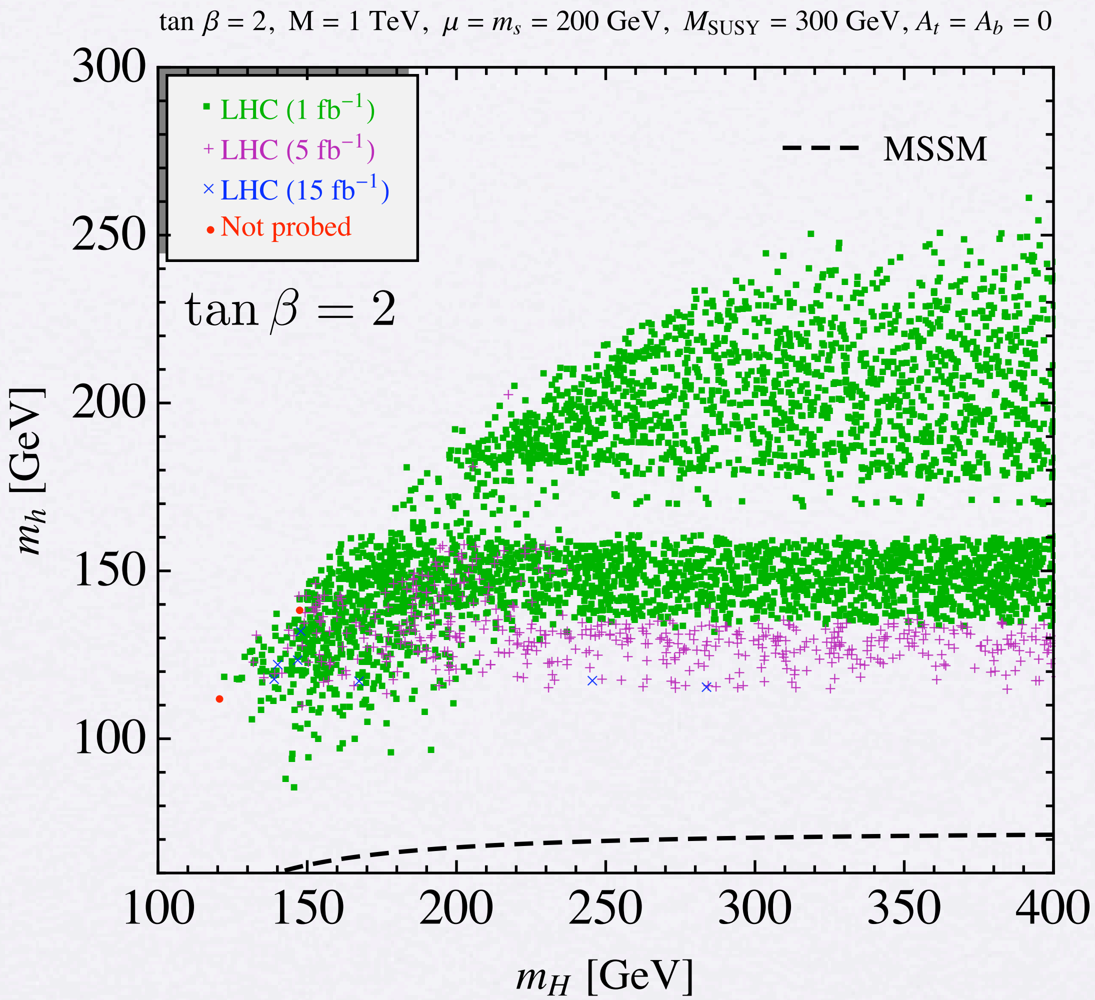
$$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \sim g^2 + \mathcal{O}(1/M^2) \quad \longleftarrow \quad \text{can be relevant!}$$

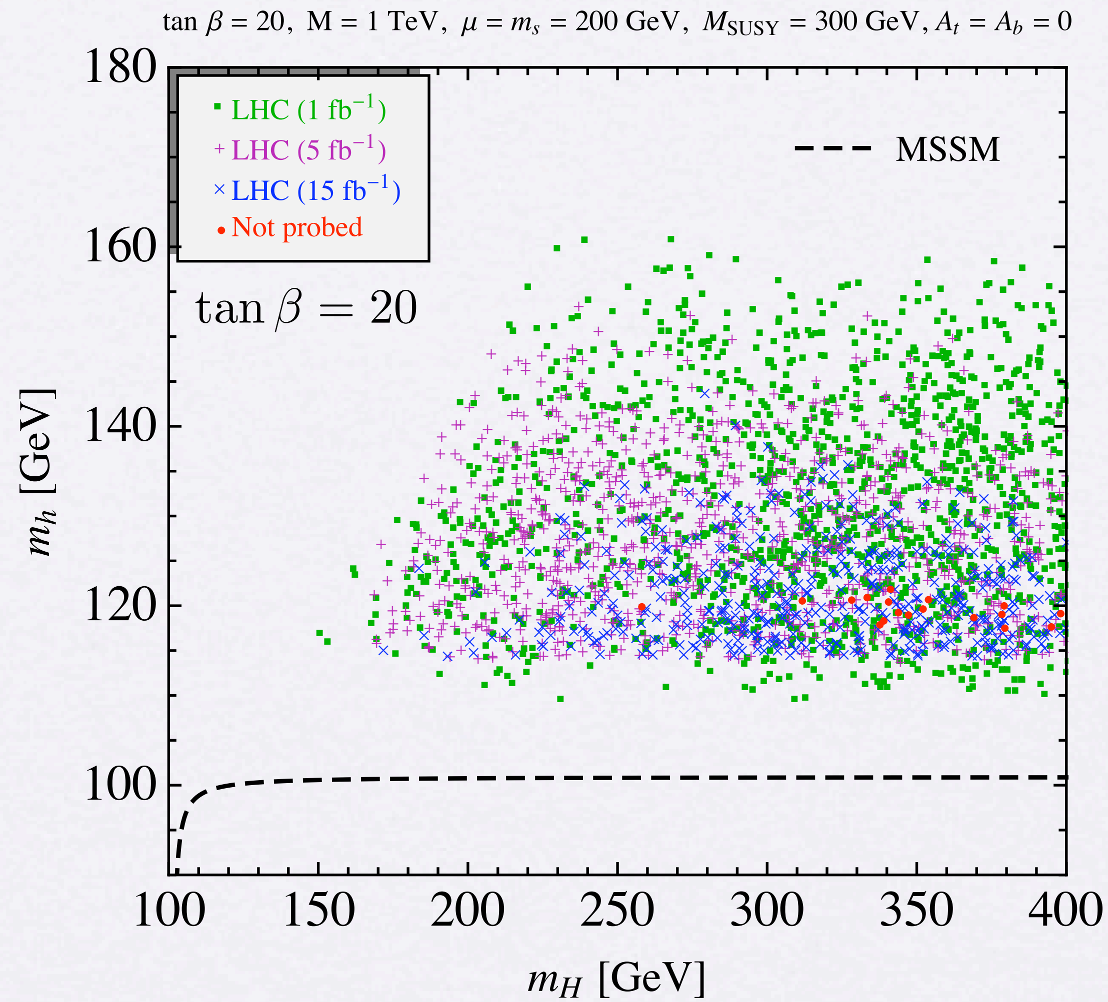
$$\lambda_5, \lambda_6, \lambda_7 \sim \mathcal{O}(1/M) + \mathcal{O}(1/M^2)$$

Heavier Higgses under Stress

(Carena, EP & Zurita, to appear)

Most recent LHC searches in $WW, ZZ, \gamma\gamma, \tau\tau, t \to H^+ b$





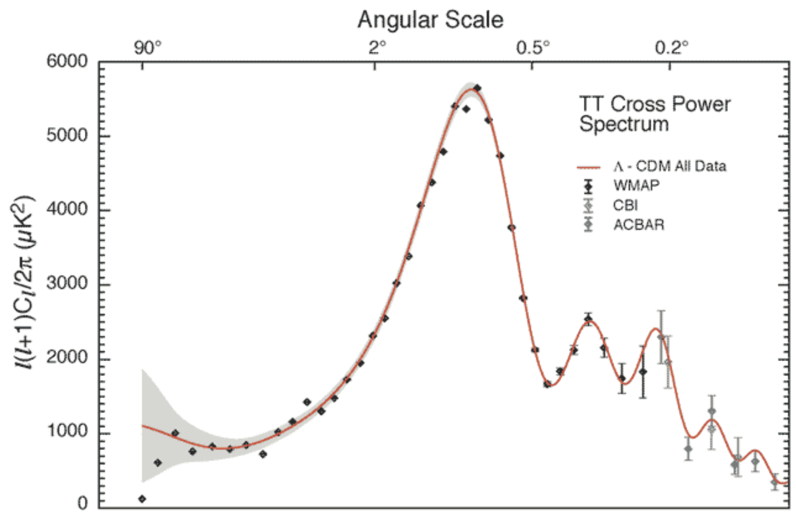
- Most model points excluded, or can be excluded with $5\ \mathrm{fb}^{-1}$ at $\tan\beta = 2$

  or $15\ \mathrm{fb}^{-1}$ at $\tan\beta = 20$

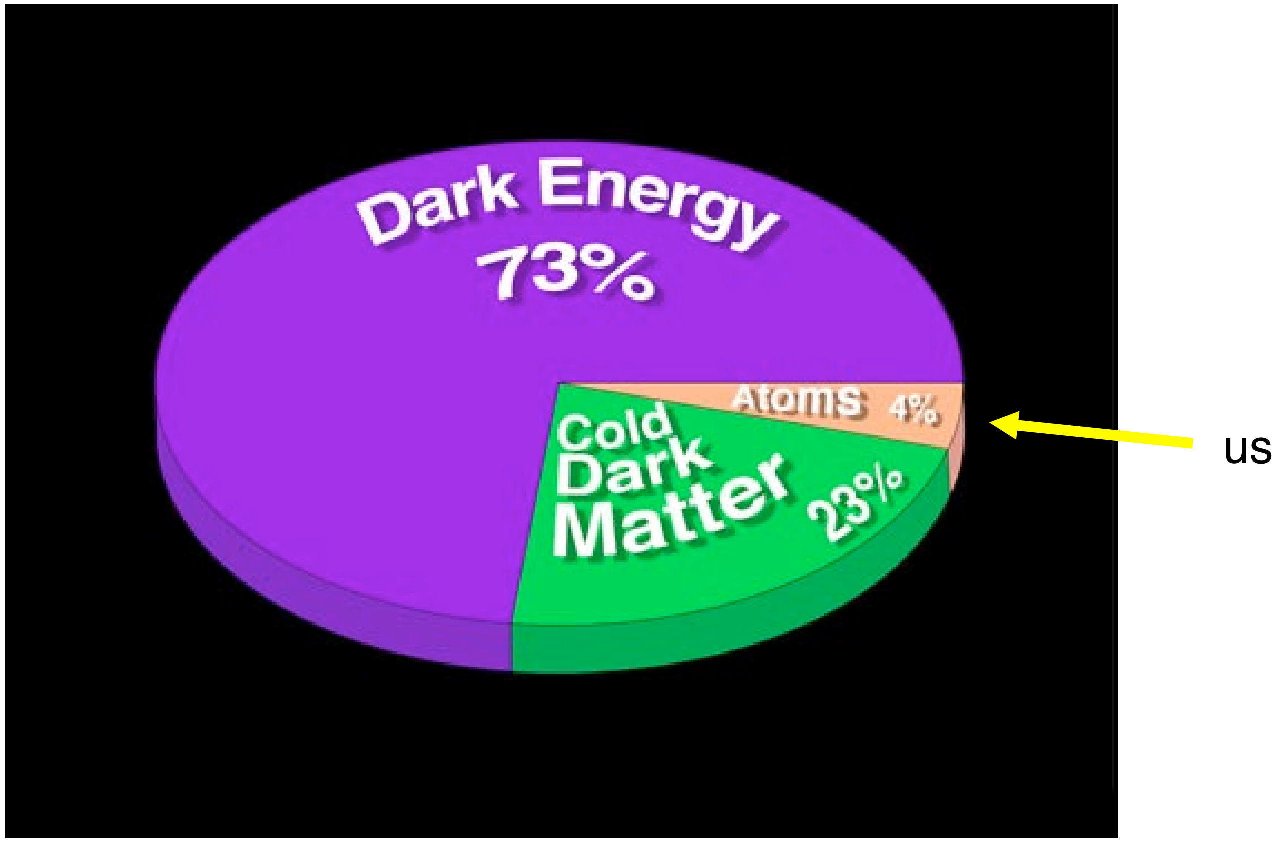
Results from WMAP

Ω_i : Fraction of critical density

Universe density $\Omega_0 = 1.02 \pm 0.02$
Dark energy density $\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density $\Omega_M = 0.27 \pm 0.05$ → Dark matter is non-baryonic
Baryon matter density $\Omega_b = 0.044 \pm 0.004$



Our Universe:



If Dark Matter is a neutral particle proceeding from the thermal bath, its density fraction is inversely proportional to its annihilation rate.

"The Weak will inherit the Universe"

Dark Matter Annihilation Rate

- The main reason why we think there is a chance of observing dark matter at colliders is that, when we compute the annihilation rate to get the proper relic density, we get a cross section

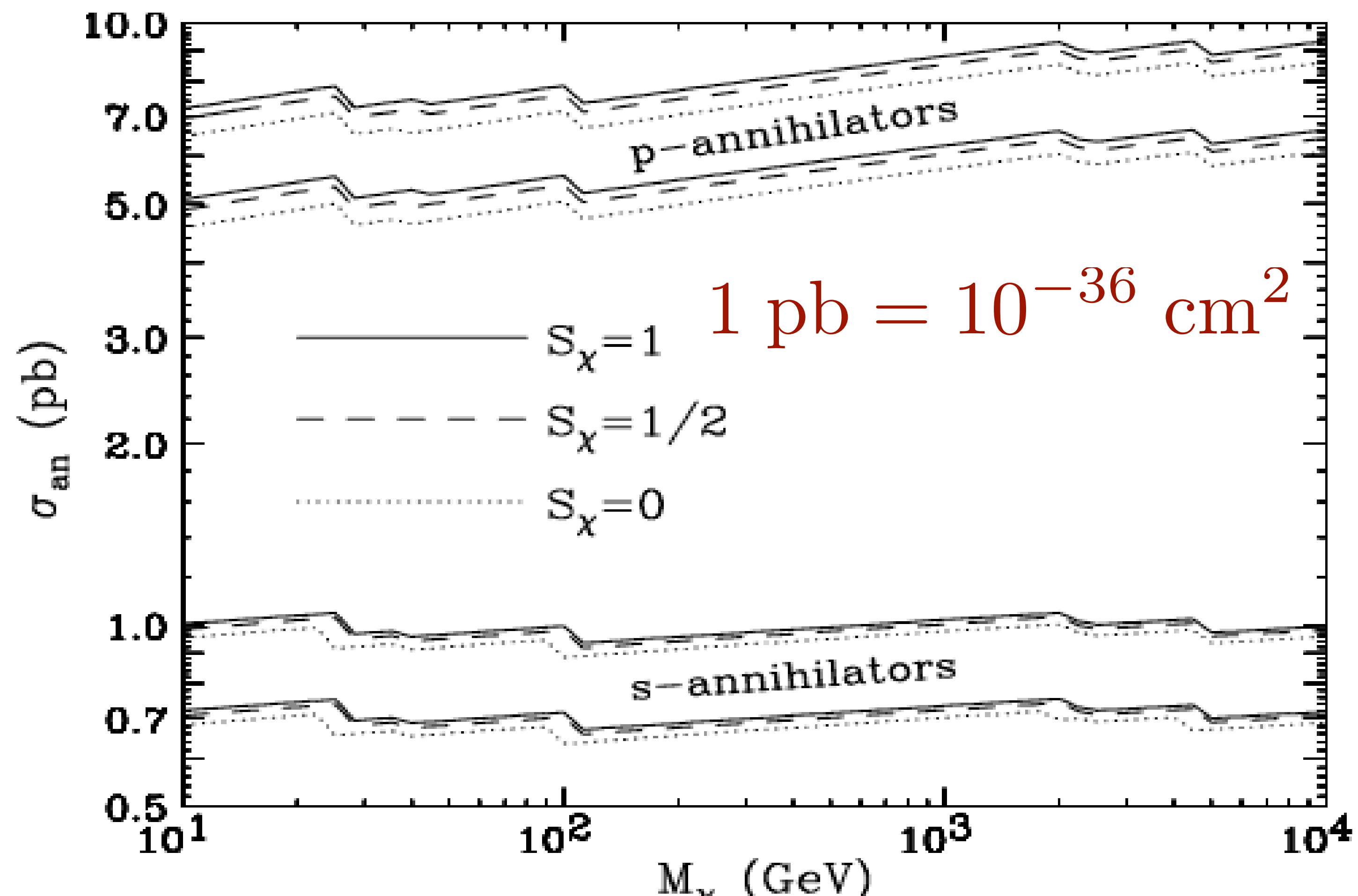
$$\sigma_{\mathrm{ann.}}(\mathrm{DM\ DM} \to \mathrm{SM\ SM}) \simeq 1\ \mathrm{pb}$$

- This is approximately

$$\sigma_{\mathrm{ann.}} \simeq \frac{\alpha_W^2}{\mathrm{TeV}^2}$$

This suggests that it is probably mediated by weakly interacting particles with weak scale masses

$$1\ \mathrm{pb} = 10^{-36}\ \mathrm{cm}^2$$



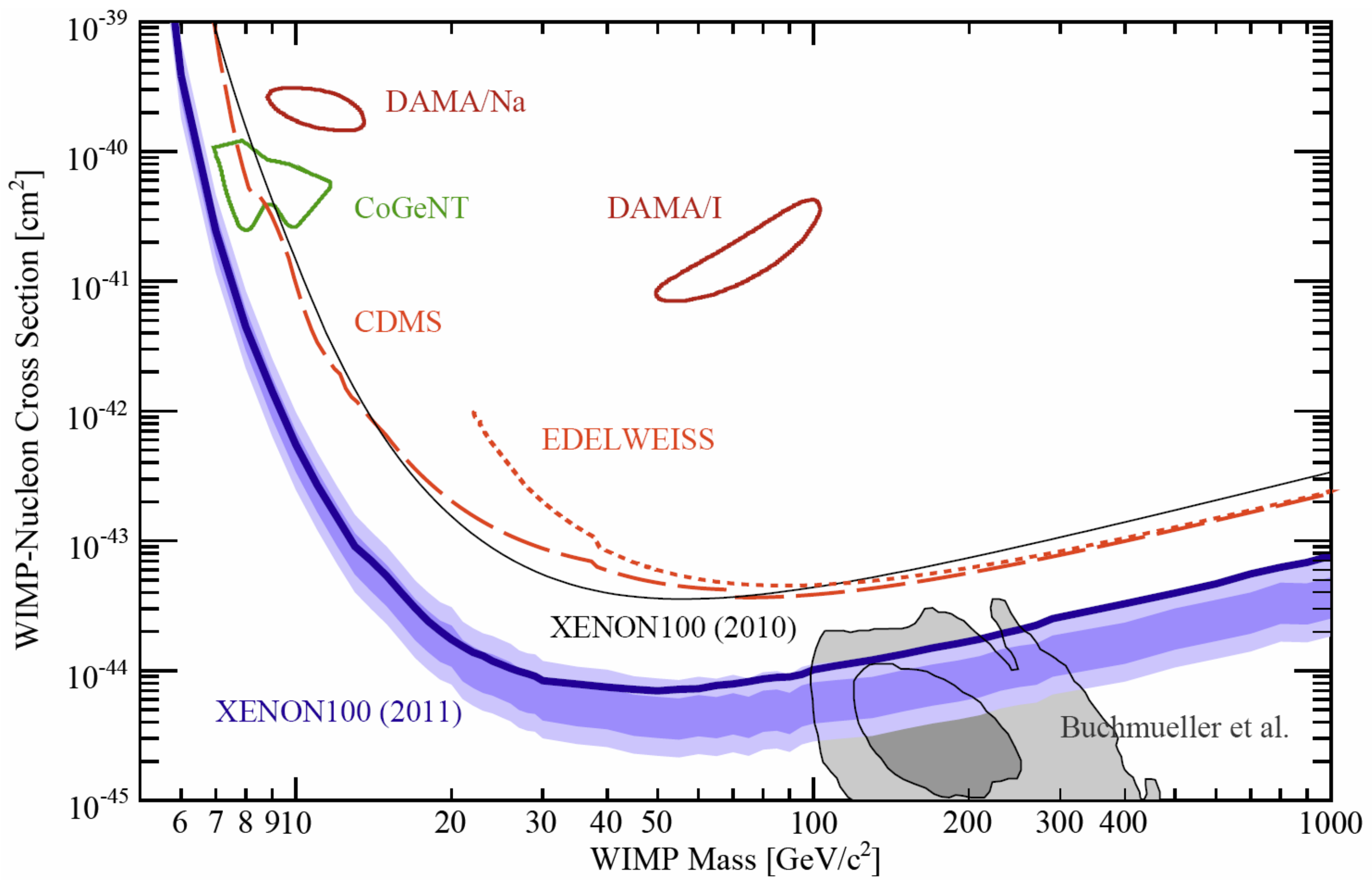
(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

- Connection of Thermal Dark Matter to the weak scale and to the mechanism of electroweak symmetry breaking

Feng

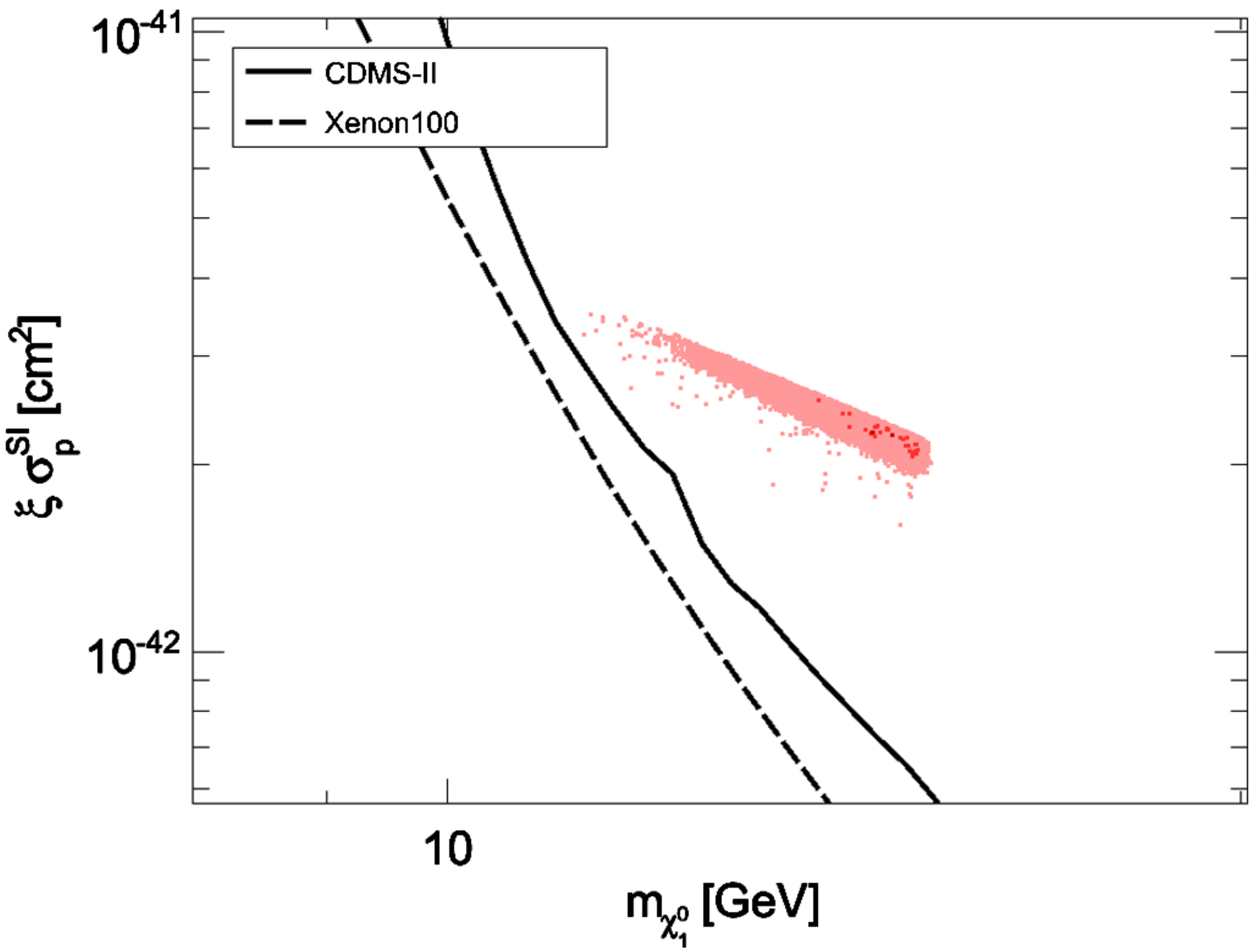
CURRENT STATUS

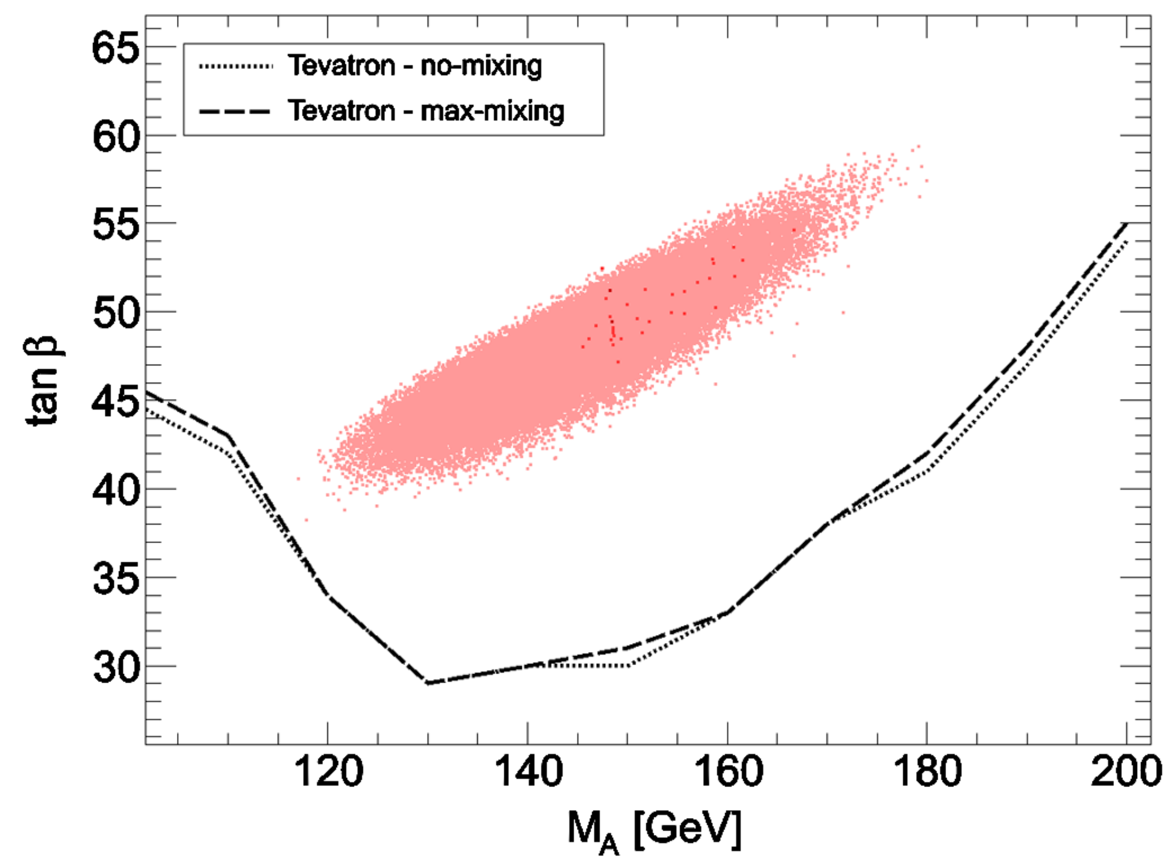
- The excitement at low cross sections stems from the confrontation of experiment with theory
- How robust and interesting are the theoretical predictions?



Light Dark Matter in the MSSM ?

D.Albornoz Vasquez, G. Belanger, C. Bœhm, A. Pukhov, and J. Silk
PHYSICAL REVIEW D **82,** 115027 (2010)





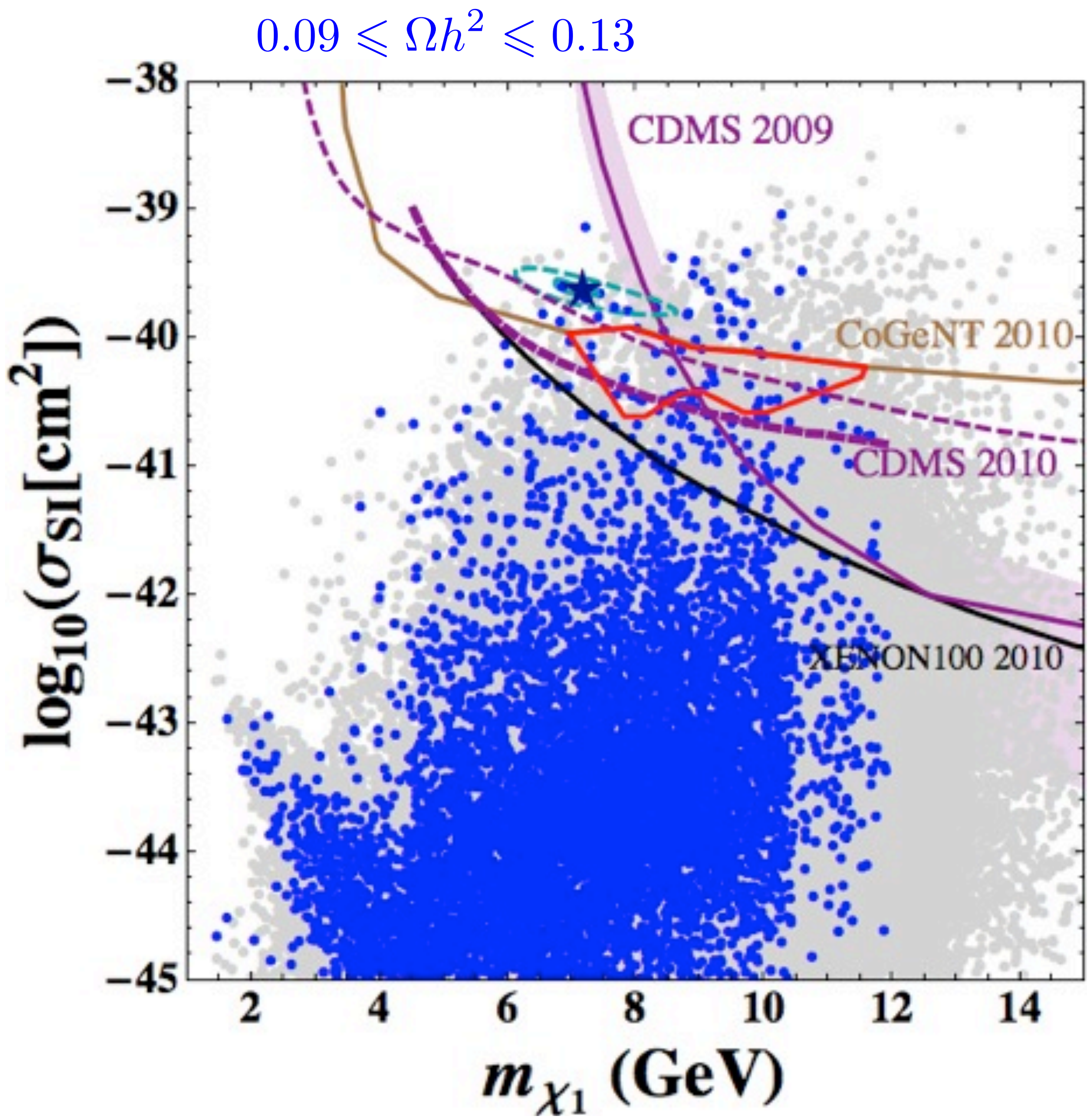
$$M_1 \in [1, 100]\ \text{GeV}, \quad M_2 \in [100, 2000]\ \text{GeV},$$
$$\mu \in [0.5, 1000]\ \text{GeV}, \quad \tan\beta \in [1, 75],$$
$$m_{\tilde{l}} \in [100, 2000]\ \text{GeV}, \quad m_{\tilde{q}} \in [300, 2000]\ \text{GeV},$$
$$A_t \in [-3000, 3000]\ \text{GeV}, \quad m_A \in [100, 1000]\ \text{GeV}.$$

Also (e.g.):
Feldman, Liu, Nath, Piem (2010)
Kuflik, AP, Zurek (2010);

Dark Light Higgs (NMSSM near the PQ symmetry limit)

Numerical Results

λ	$\kappa(10^{-3})$	$A_\lambda(10^3)$	A_κ	μ	$\tan\beta$	m_{h_1}
0.1205	2.720	2.661	-24.03	168.0	13.77	0.811
m_{a_1}	m_{χ_1}	m_{h_2}	Brhh	Braa	Ωh^2	$\sigma_{\rm SI}(10^{-40})$
16.7	7.20	116	0.158%	0.310%	0.112	2.34



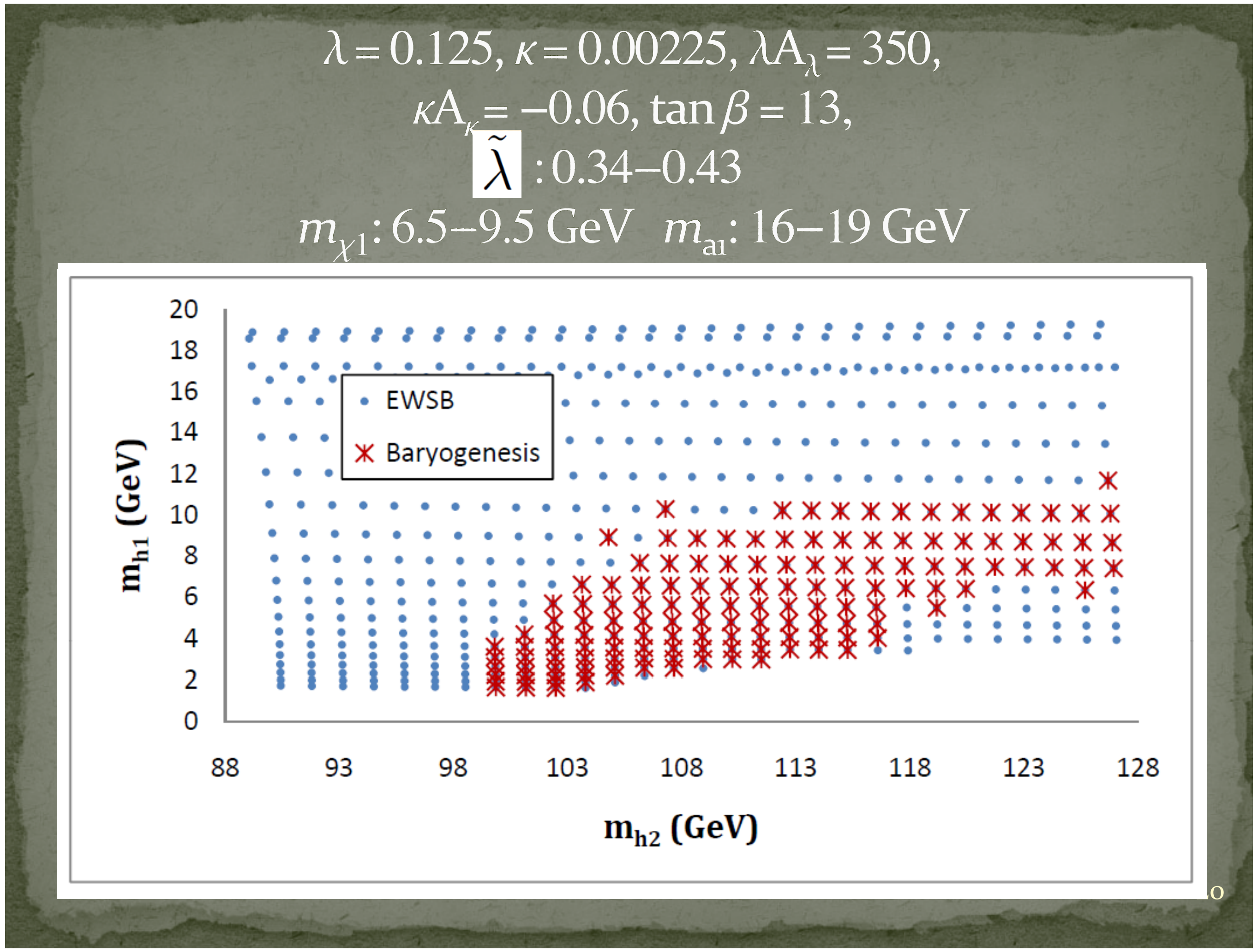
$$0.05 \leqslant \lambda \leqslant 0.15, \quad 0.001 \leqslant \kappa \leqslant 0.005,$$
$$|\varepsilon'| \leqslant 0.25, \quad -30\mathrm{GeV} \leqslant A_\kappa \leqslant -15\mathrm{GeV},$$
$$5 \leqslant \tan\beta \leqslant 50, \; 100\mathrm{GeV} \leqslant \mu \leqslant 250\mathrm{GeV}$$

- The blue points fall in a 3 sigma range of the observed relic density.
- All points have passed the current exp. bounds of flavor physics, meson decays, and collider exp.

T. Liu

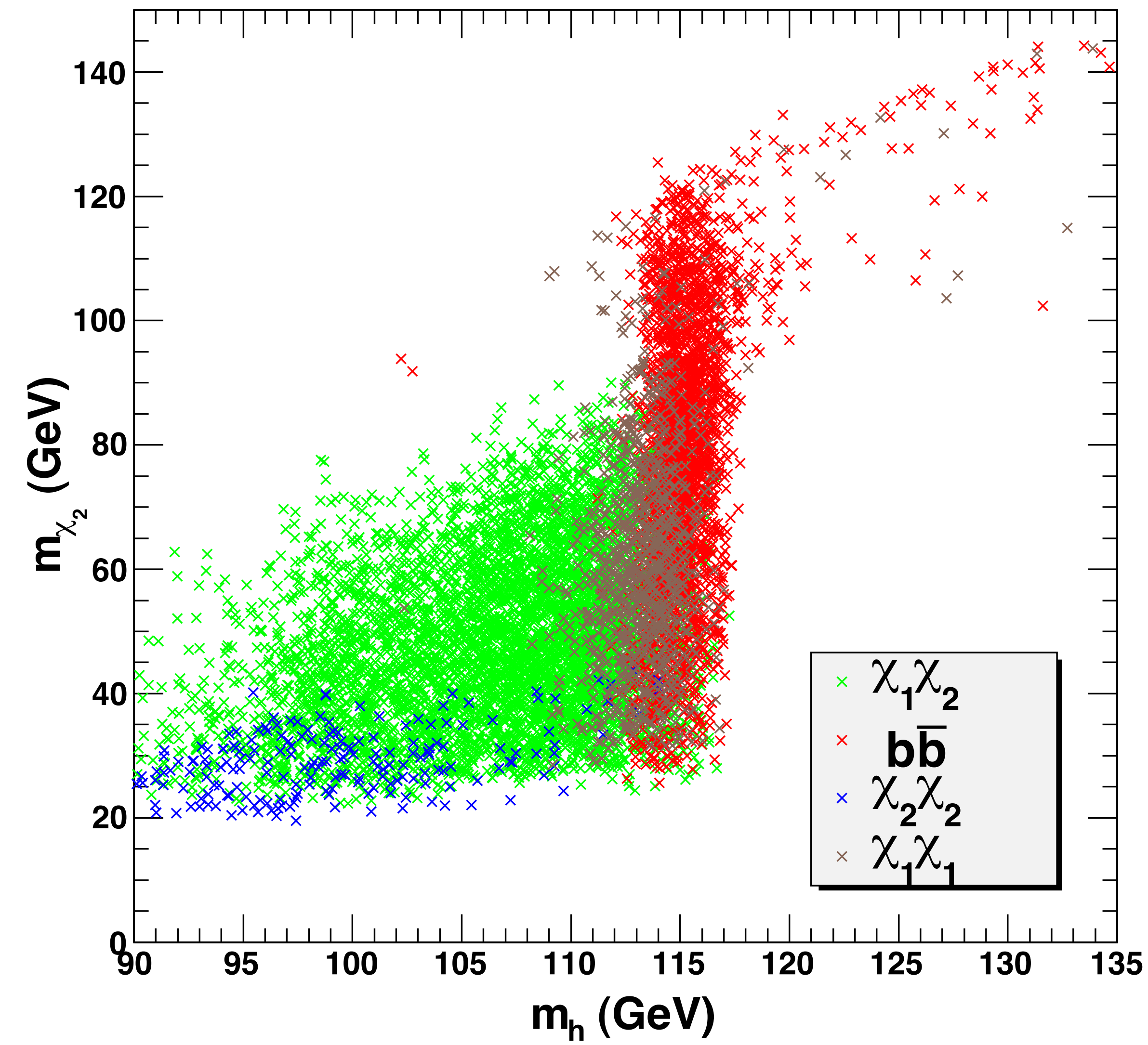
P. Draper, T.L., C. Wagner, L.T. Wang and H. Zhang, Phys. Rev. Lett. 106 (2011)

N. Shah



A strongly first order phase transition may be obtained (red dots).
Consistency with COGENT demands mh1 close to 1 GeV. Only possible for mh2 smaller than LEP limit.

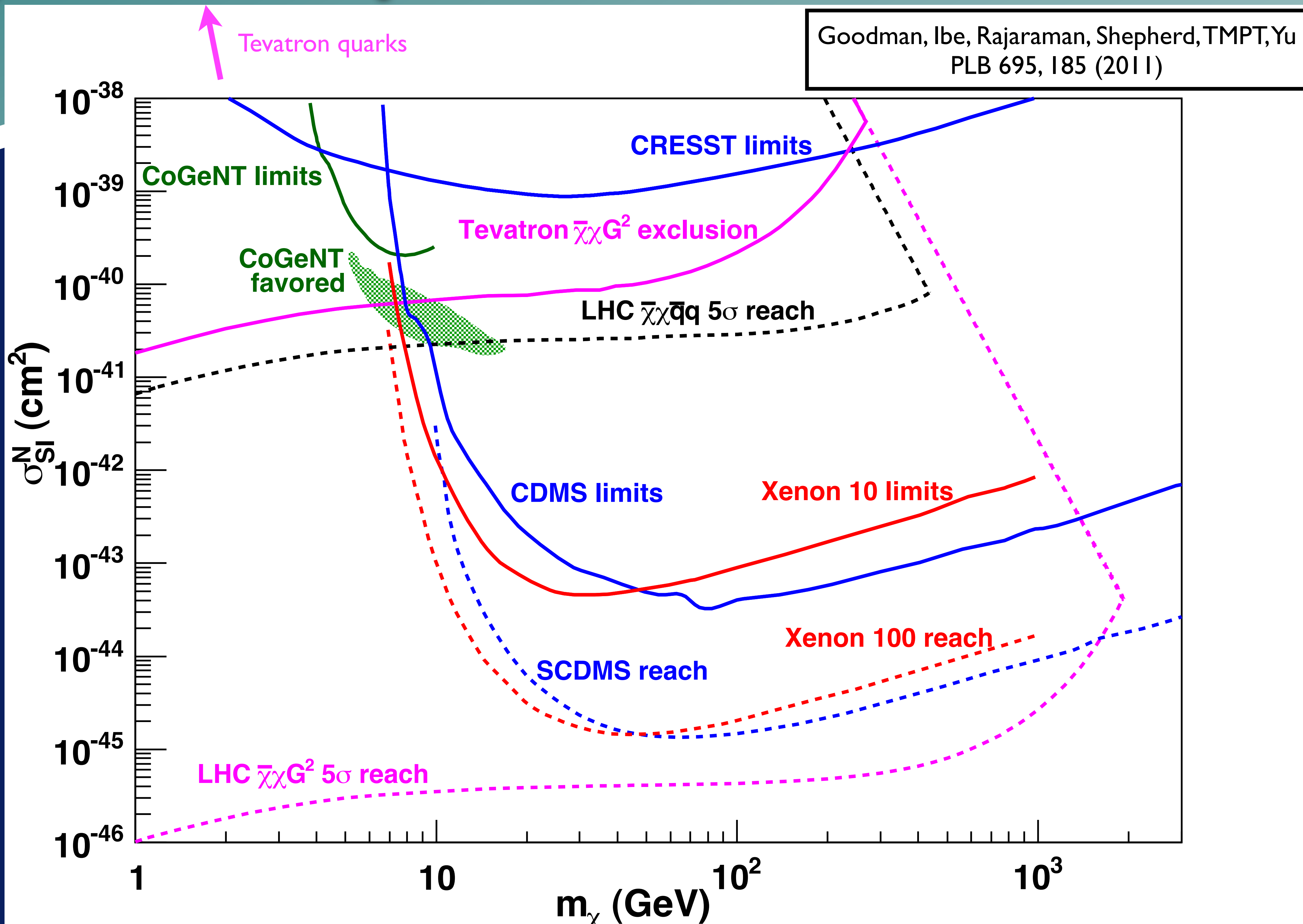
T. Liu



LEP limit may be avoided due to the existence of additional decay modes

Spin-Independent

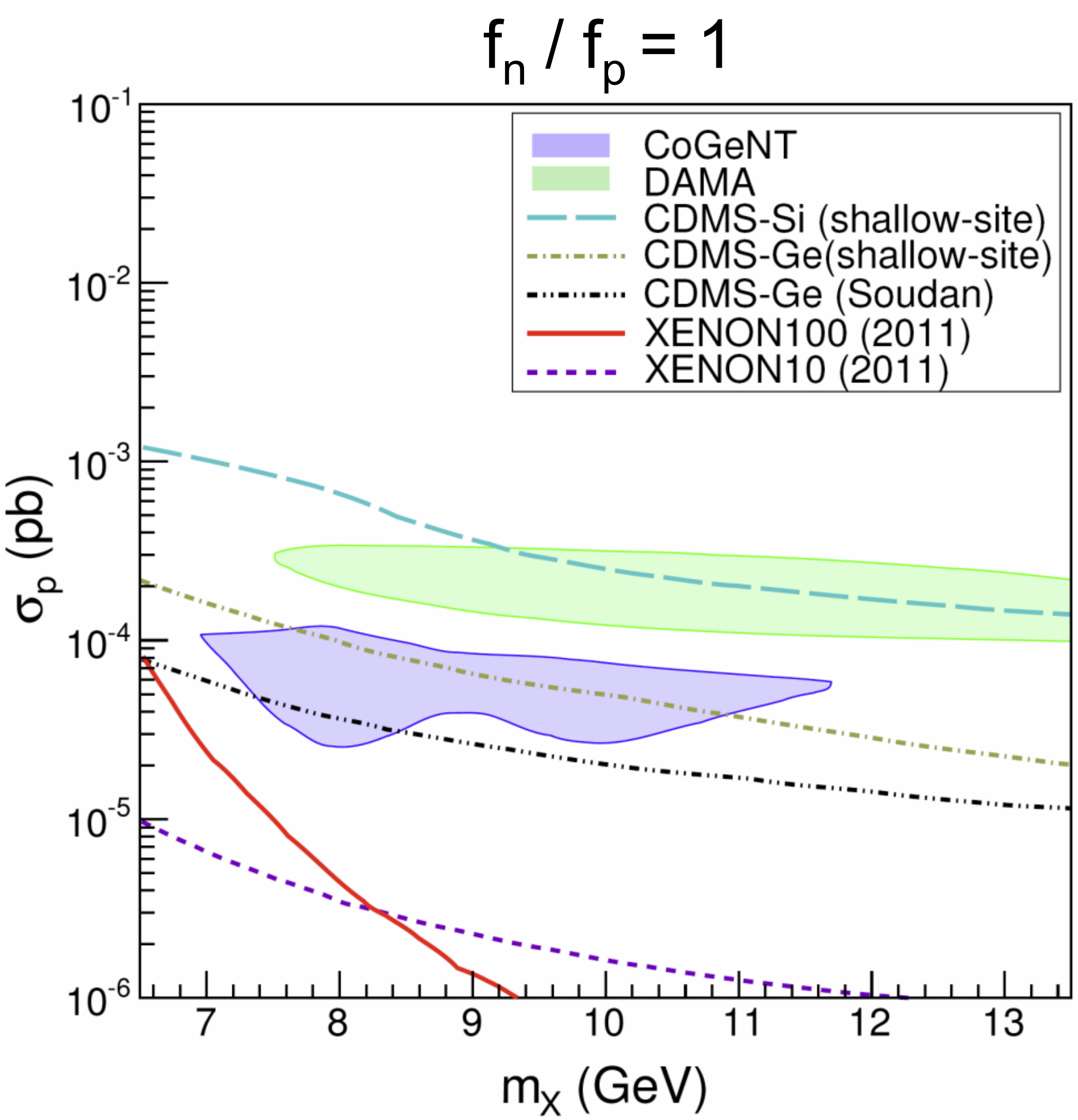
T. Tait

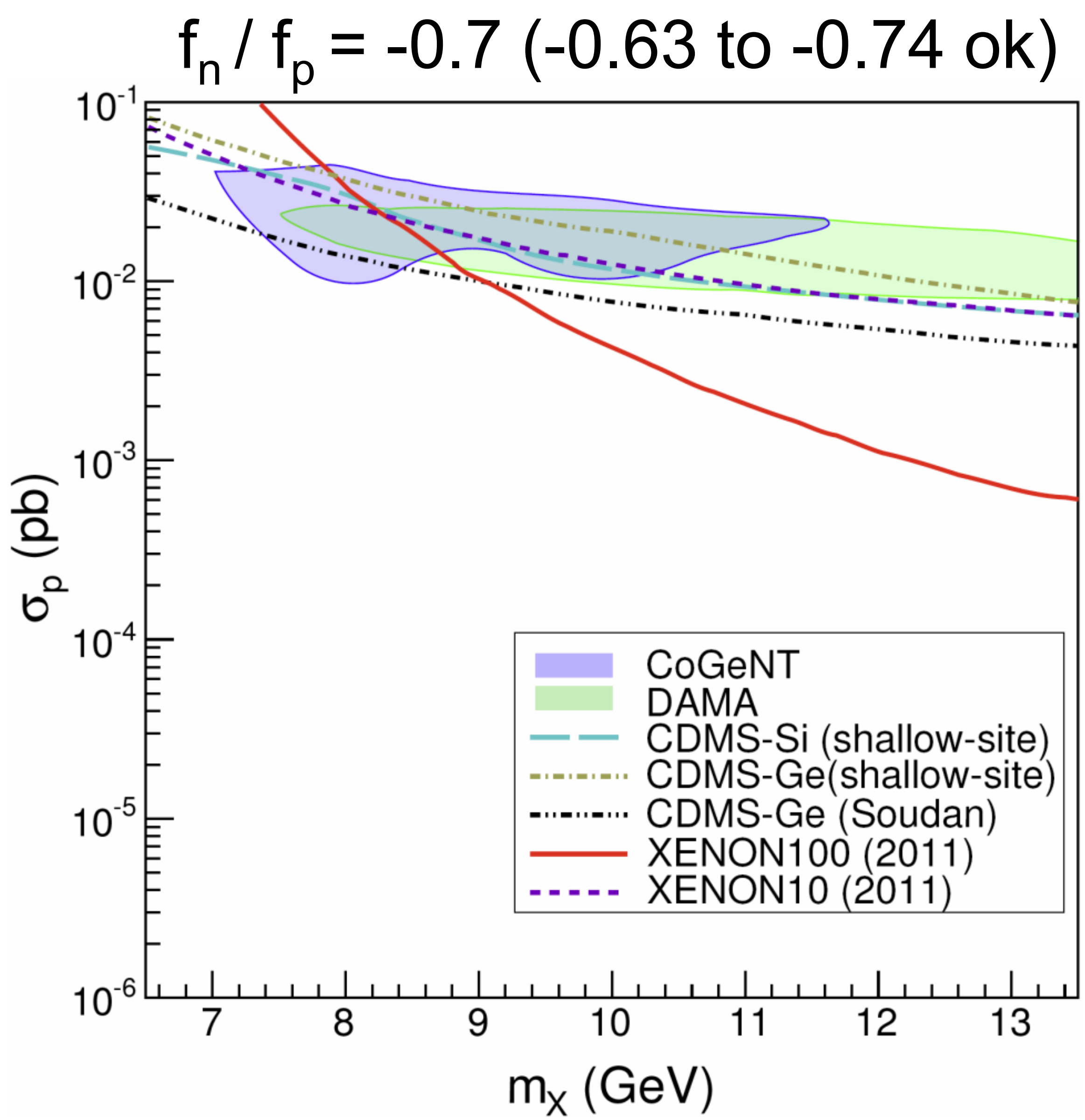


Similar results from the FNAL group: Bai, Fox, Harnik 1005.3797 [JHEP]!

Feng

RECONCILING XENON/DAMA/COGENT





Nima Arkani-Hamed

Hidden Symmetries in Nature, not obvious in Lagrangian Formalism.

They allow to simplify tremendously amplitude calculations

They may be essential to make progress towards our understanding of the connection of Gauge Theories with Quantum Gravity

To make progress, we should all start studying Galois Motivitic Theories, and start talking to Russian Mathematicians

http://en.wikipedia.org/wiki/Motive_(algebraic_geometry)

New Physics Signatures ?

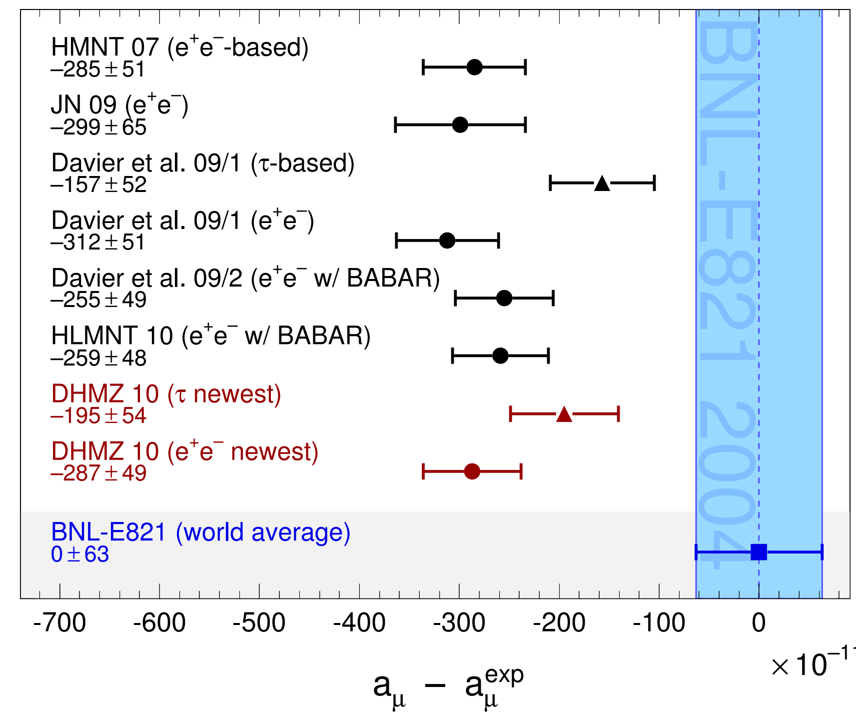
Observed HEP Anomalies

Signals which are two to three standard deviations away from the expected SM predictions.

- 100 GeV Higgs signal excess. Rate about one tenth of the corresponding SM Higgs one.
- 115 GeV Higgs signal, seen only by Aleph experiment at LEP.
- DAMA/LIBRA annual modulation signal, direct DM detection searches (sodium iodide NaI scintillation crystal). COGENT experiment sees a compatible signal, disputed by XENON
- Anomalous magnetic moment of the muon.
- Forward-backward asymmetry of the bottom quark at LEP. (Dermisek, Kim)
- Forward-backward asymmetry of the top quark at the Tevatron. (Kim, Jung, Zhu)
- Apparent anomalous neutrino results, in MiniBoone, MINOS, LSND and reactor fluxes. (Kopp)
- B physics : CP-violating dimuon charge asymmetry at D0
- Anomalies observed in $B \to K\pi, \quad B \to \tau\nu \;\; \text{and} \;\; B \to K l^+ l^-$ transitions (Heinonen)
- Apparent 214 MeV muon pair resonance in the decay $\Sigma \to p\, \mu^+ \mu^-$
- Anomalous W + 2 jets events at CDF (Omura, Anchordoqui, Spethman)
- Proton radius difference measured in electron or muon hydrogen atoms ? (R. Hill, G. Paz'11)

Muon Anomalous Magnetic Moment

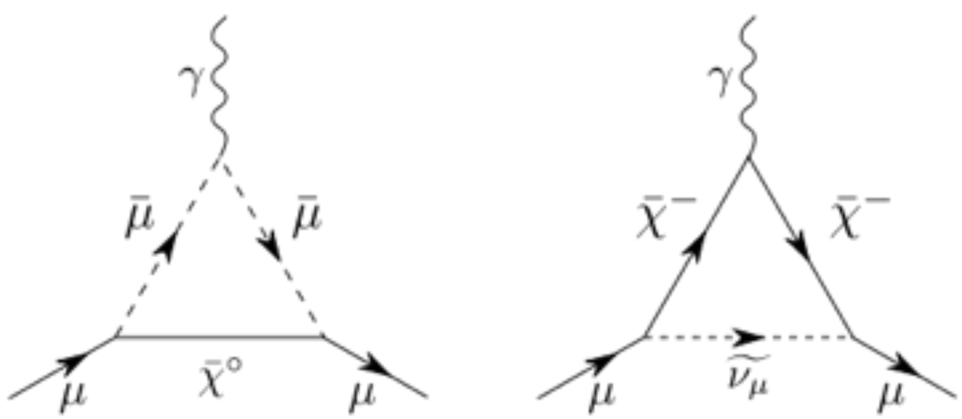
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level



$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287(63)(49) \times 10^{-11}$$

3.6σ Discrepancy — A. Hoecker'11; Boughezal, Melnikov'11

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \simeq 15 \times 10^{-10} \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2 \tan\beta$$

M. Carena, G. Giudice, C. E.M. Wagner '96

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

Anomalies may be resolved by different Physics

Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

G. Segre'10

Conclusions

Theoretical ideas and models abound.
No compelling guidance from (fantastic) experiments yet.

In the coming years, the Higgs and the WIMP hypothesis will be tested by the Tevatron, the LHC and by direct and indirect dark matter detection experiments.

Signals of other type of new physics may be revealed soon.

We should expect to get a more clear picture by SUSY 2012 in Beijing

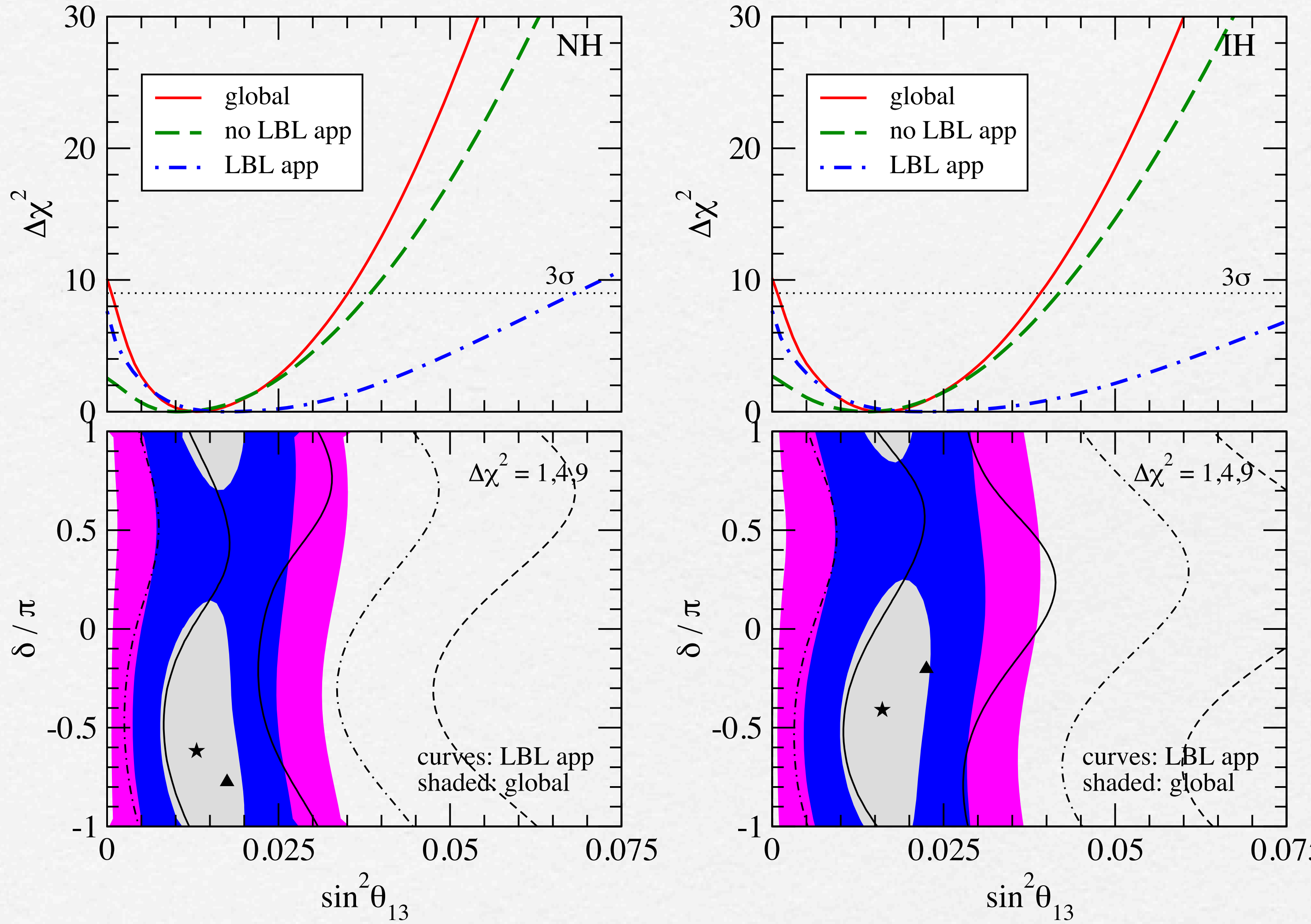
See you there !

Neutrino Physics

Global Fits

Schwetz, Tortola, Valle '11

parameter	best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.59^{+0.20}_{-0.18}$
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$



c.f.Fogli, Lisi, Marrone,Palazzo, Rotunno'11

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35

Harrison, Perkins, Scott; Xing

Tri-bimaximal

Excluded by T2K r≠0

$$s = a = r = 0$$

$$U_{TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} P,$$

$$M_\nu = \frac{v^2 AA^T}{M_A} + \frac{v^2 BB^T}{M_B}$$

$$A \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

hep-ph/0506297

CSD

King; Antusch, Boudjemaa, K; Morisi, Patel, Peinado

Tri-bimaximal-reactor

OK

$$s = a = 0, \;\; r \neq 0$$

$$U_{TBR} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} r e^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1 + re^{i\delta}) & \frac{1}{\sqrt{3}}(1 - \frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}}(1 - re^{i\delta}) & -\frac{1}{\sqrt{3}}(1 + \frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \end{pmatrix} P$$

$$M_\nu = \frac{v^2 AA^T}{M_A} + \frac{v^2 BB^T}{M_B}$$

$$A \propto \begin{pmatrix} re^{-i\delta} \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

0903.3199

PCSD

Lam; Albright, Rodejohann

Trimaximal1

OK for range of δ

$$a = r\cos\delta \qquad s = 0$$

$$U_{\mathrm{TM}_1} = P' \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} r e^{-i\delta} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1 - \frac{3}{2} r e^{i\delta}) & \frac{1}{\sqrt{2}}(1 + r e^{-i\delta}) \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1 + \frac{3}{2} r e^{i\delta}) & -\frac{1}{\sqrt{2}}(1 - r e^{-i\delta}) \end{pmatrix} P$$

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \text{ or } B \propto \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

CSD2 1108.4278

Haba, Watanabe, Yoshioka; He, Zee;
Grimus, Lavoura; Albright, Rodejohann

Trimaximal2

OK for larger range of δ

$$a = -\frac{1}{2} r\cos\delta \qquad s = 0$$

$$U_{\mathrm{TM}_2} = P' \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} r e^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1 + \frac{3}{2} r e^{i\delta}) & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}(1 - \frac{1}{2} r e^{-i\delta}) \\ -\frac{1}{\sqrt{6}}(1 - \frac{3}{2} r e^{i\delta}) & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}}(1 + \frac{1}{2} r e^{-i\delta}) \end{pmatrix}$$

$$M_\nu = \frac{v^2 A A^T}{M_A} + \frac{v^2 B B^T}{M_B}$$

$$A \propto \begin{pmatrix} r e^{-i\delta} \\ 1 - r e^{-i\delta} \\ -1 \end{pmatrix} \quad B \propto \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\frac{AA^T}{M_A} \gg \frac{BB^T}{M_B}$$

PCSD2 1011.6167

Family Symmetry

$$\frac{1}{3}\begin{pmatrix}-1 & 2 & 2\\ 2 & -1 & 2\\ 2 & 2 & -1\end{pmatrix} \quad \begin{pmatrix}1 & 0 & 0\\ 0 & \omega^2 & 0\\ 0 & 0 & \omega\end{pmatrix} \quad \mp\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{pmatrix}$$

- TB mixing respects discrete symmetry $S, T, U \in S_4$

$$SM^\nu S = M^\nu \quad TM^E T = M^E \quad UM^\nu U = M^\nu$$

Lam

- TM2 mixing respects discrete sym $S, T \in A_4$

$$SM^\nu S = M^\nu \quad TM^E T = M^E$$

- Since TB mixing is a good approximation, this suggests an S4 family symmetry broken to A4

$$S_4 \to A_4$$

King, Luhn **1107.5332 JHEP**

Assumptions on the Susy-breaking sector (SBS)

Strongly coupled theory generically defined by:

- Energy scale (mass gap): Λ ~TeV
- "Number of colors": N (number of messengers in GMSB)
- Susy breaking of order one:
  - ➡ Susy-breaking splittings also of order ~ Λ
  - ➡ hard and soft Susy-breaking terms of the same order

To get predictions, beyond NDA estimates, we will use the AdS/CFT correspondence:

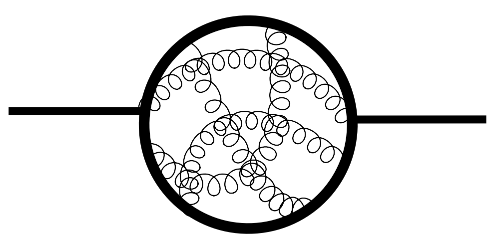
Strong sector ➠ Warped Extra-dimension

Higgs sector

1) MSSM Higgs doublets coupled to the SBS:

$$g_i \int d^2\theta \; H_i \mathcal{O}_i$$

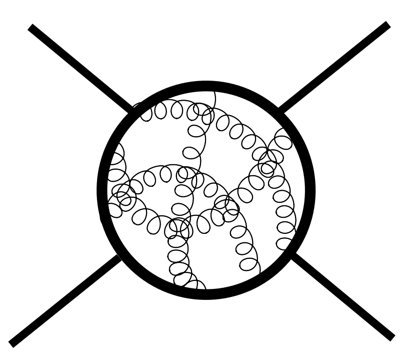
Higgs potential terms:



$$m_i^2 \sim \frac{g_i^2 N \Lambda^2}{16\pi^2} \simeq \Lambda^2 \epsilon_{H_i}^2$$

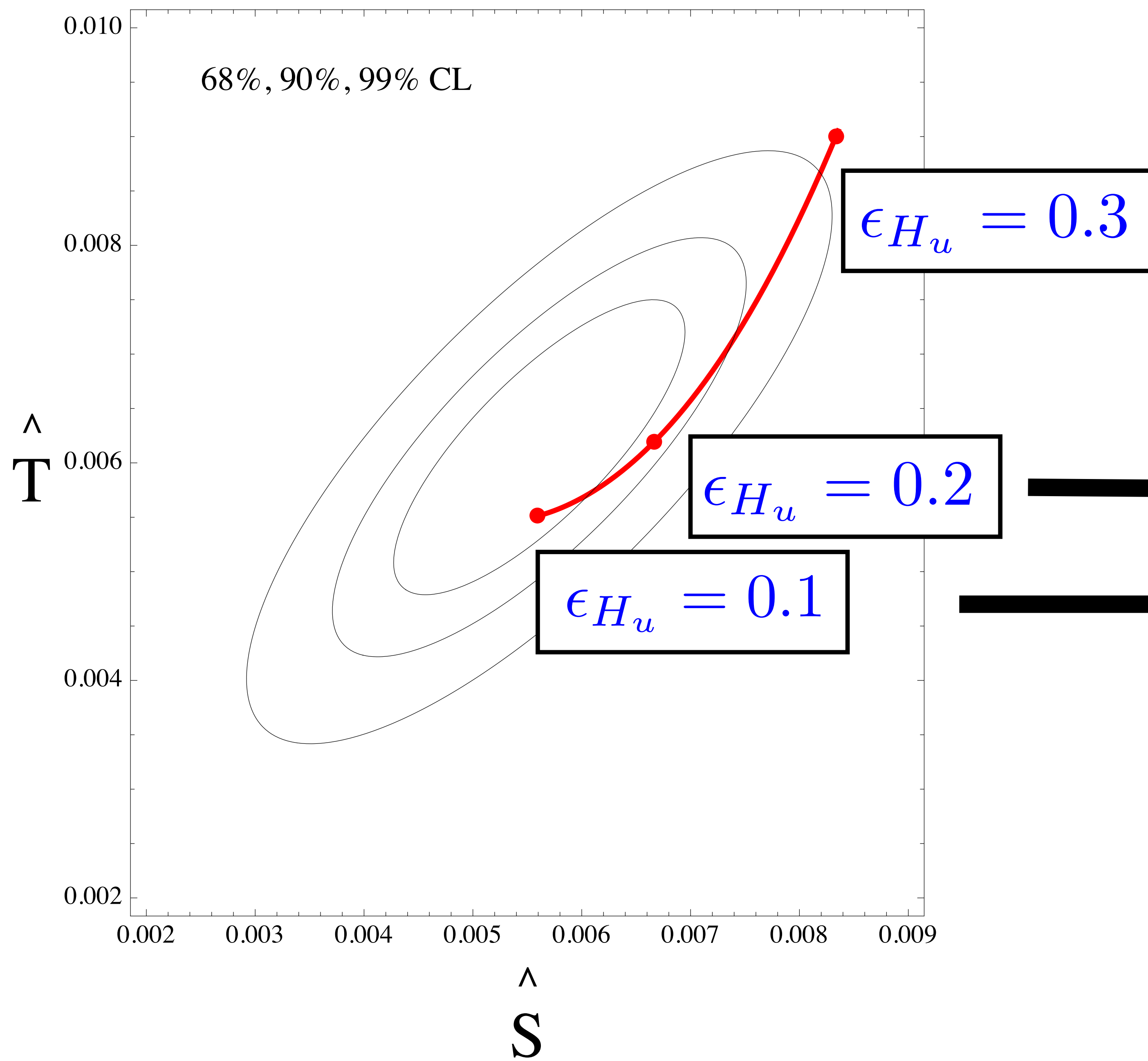
$$\epsilon_{H_i} \sim \frac{g_i}{g_{st}} \qquad g_{st} \sim 4\pi/\sqrt{N}$$

degree of mixing with the strong sector



$$\Delta\lambda_i \sim \frac{g_i^4 N}{16\pi^2} \simeq \frac{16\pi^2}{N} \epsilon_{H_i}^4$$

$N = 6$ $\qquad$ $\Lambda = 1\ \text{TeV}$



$m_h \sim 193$ Ge

$m_h \sim 120$ GeV

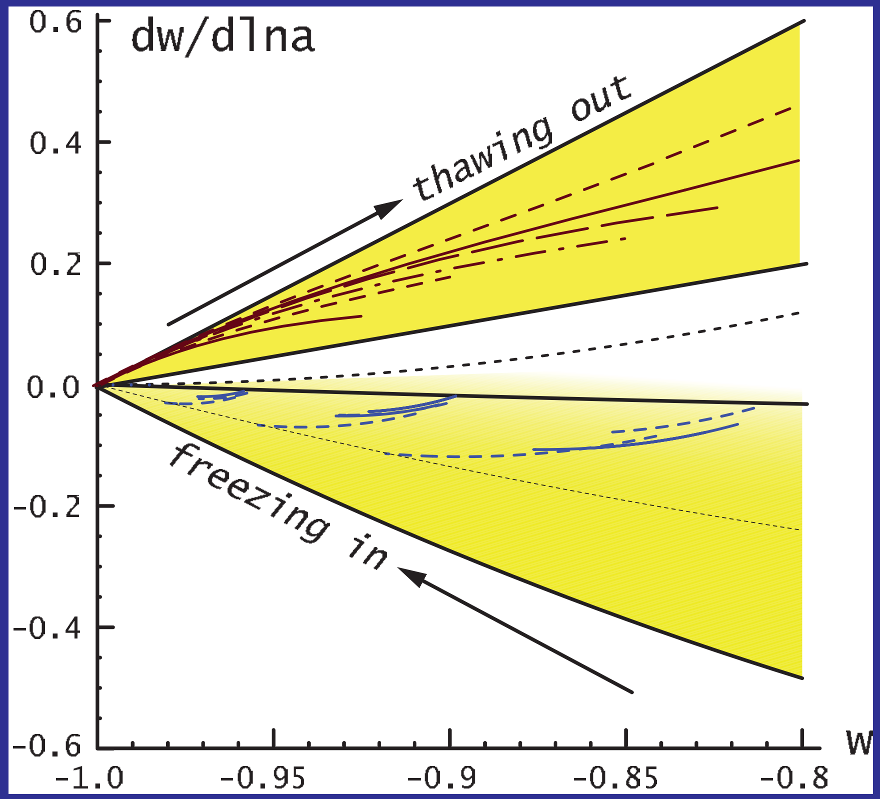
$m_h \sim 91$ GeV

at tree-level

Quintessence

- Perhaps the true cosmological constant is zero and we are rolling in a (very!) flat direction of a landscape like inflation [but what protects a $m \sim H_0 \sim 10^{-33}$eV mass and small couplings?]
- Two degrees of freedom:
  potential energy (driving acceleration)
  kinetic energy (associated with rolling)
  dynamical dark energy
- Typical models:
  thawing -
  frozen by Hubble drag,
  released to roll
  freezing
  rolling/tracking early
  on and slowing to potential domination
  [possibly trading coincidence with features in potential]

Caldwell & Linder (2005)



Modified Forces

- Extra scalar propagating degree of freedom
- Cosmological IR modification hidden from local constraints on gravity and fifth forces → non-linear mechanism (strong interactions or changes in the potential or coupling)

  Chameleon mechanism (running mass or coupling)

  Vainshtein mechanism (strong coupling, derivative interactions)
- Concrete (but toy) models that exhibit these

  Modified Action $f(R)$

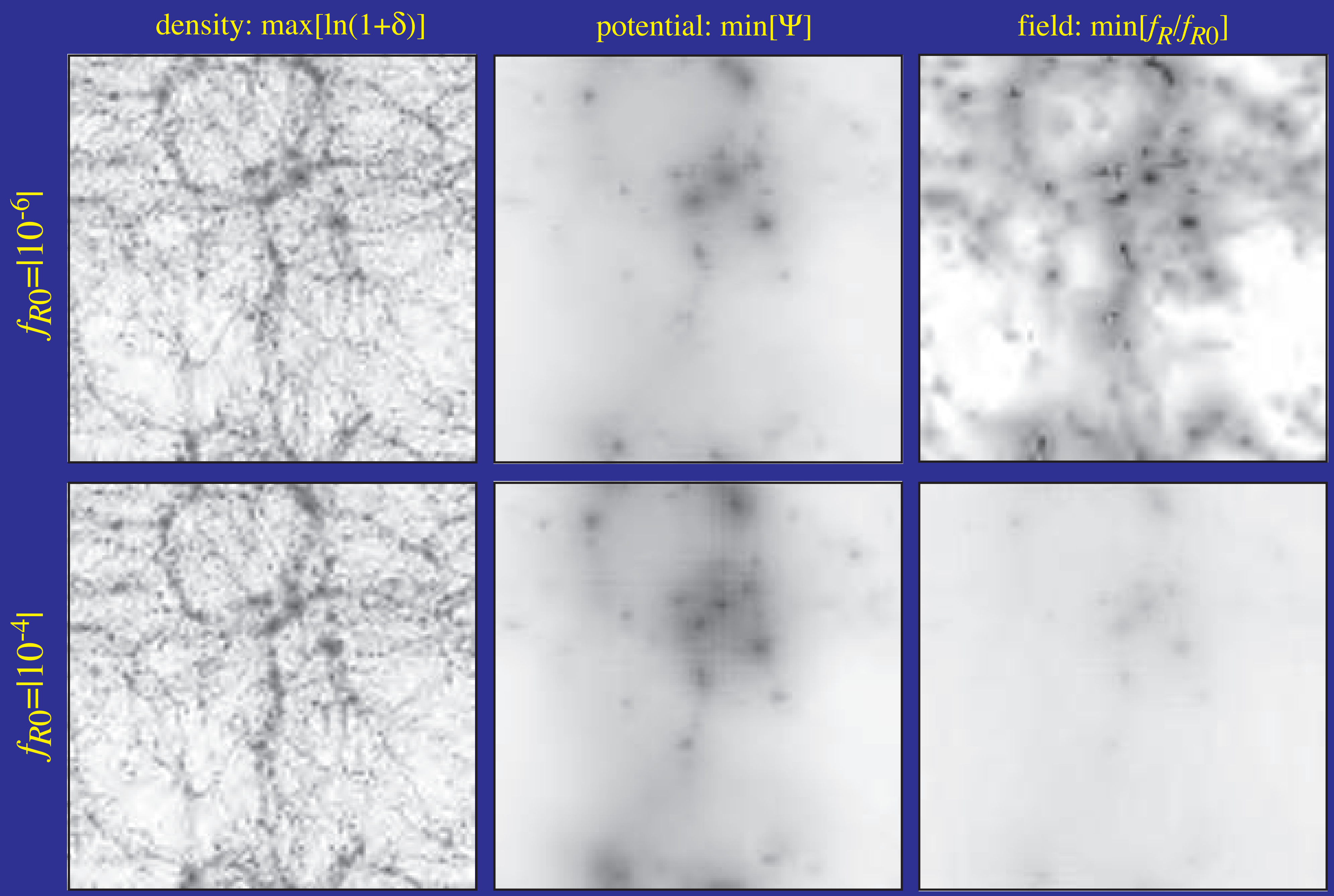
$$S = \int d^4x \sqrt{-g} \left[\frac{R + f(R)}{16\pi G} + \mathcal{L}_{\rm m} \right]$$

  Dvali-Gabadadze-Porrati (DPG) Braneworld

$$S = \int d^5x \, \sqrt{-g} \left[\frac{{}^{(5)}R}{2\kappa^2} + \delta(\chi) \left(\frac{{}^{(4)}R}{2\mu^2} + \mathcal{L}_m \right) \right]$$

Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing



Oyaizu, Lima, Hu (2008)

Massive Gravity

- DGP model motivated re-examination of massive gravity models
  [de Rham, Gabadadze, et al, Koyama et al, Hassan & Rosen (2010-2011)]
- Graviton mass $\sim H_0$ provides self-acceleration

$$H^2 = m^2 + \frac{8\pi G}{3}\rho$$

  while also not seeing the cosmological constant contribution "degravitation"

- Key: add extra terms to Fierz-Pauli action to make it nonlinearly ghost free [Arkani-Hamed, Georgi, Schwartz (2003)], exhibit Vainshtein strong coupling (Galileon symmetry, restoring vDVZ continuity)

$$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}\left(R + m^2[\mathcal{L}^{(2)}(\mathcal{K}) + \alpha_3\mathcal{L}^{(3)}(\mathcal{K}) + \alpha_4\mathcal{L}^{(4)}(\mathcal{K})]\right)$$

  with $\mathcal{K}^\mu_\nu = \delta^\mu_\nu + \sqrt{g^{\mu\alpha}\partial_\alpha\phi^a\partial_\nu\phi^b\eta_{ab}}$

- Much progress in the last year! stay tuned...

New: Stringy constraints & matter beyond the MSSM

[M.C., J. Halverson, P. Langacker,1108... tonight on hep-ph]

→ c.f., also J. Halverson's talk in the morning parallel session

I.Classify all possible MSSM quivers (three, four stacks)
study the additional matter needed to be compatible
with the global constraints - stringy inputs on exotic matter

3-stack analysis: global conditions ($T_{a,b,c}$=0) constraining, e.g., MSSM w/

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c \qquad T_a = 0 \qquad T_b = \pm 2n \qquad T_c = 0\, mod\, 3 \qquad \text{with } n \in \{0,\ldots,7\},$$

w/ preferred additions: quasi-chiral Higgs pairs, MSSM singlets
hyperchargeless SU(2) triplets,&
various quark anti-quark pairs, all w/ integer el. ch.;
one (massless) Z' quiver

4-stack analysis: richer structure
sizable number of quivers w/ Z', including leptophobic (tuned);
additional structures: possible SH_uH_d,; ν-masses;
exotics w/ fractional el. ch. …

II. Work in progress on axigluons w/ (stringy) quiver embedding

• 105 3-node quivers (≤ 5 additions)

Multiplicity	Matter Additions				
4	$\Box\Box_b,\ (1,3)_0$	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$			
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$			
4	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\Box\Box_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(\overline{a},\overline{b}),\ (\overline{3},2)_{-\frac{1}{6}}$
4	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$			
4	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$		
4	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$\boxminus_a,\ (\overline{3},1)_{\frac{1}{3}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\Box\Box_c,\ (1,1)_1$
4	$\Box\Box_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$		
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\boxminus_b,\ (1,1)_0$				
4	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	
4	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\Box\Box}_b,\ (1,3)_0$	$\overline{\boxminus}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	$\boxminus_b,\ (1,1)_0$	